STUDY OF THE DYNAMIC RESPONSE OF ORGANIC LIGHT EMITTING DIODES AND CROSSTALK IN PASSIVE MATRIX DISPLAYS

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by

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to the

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January 2002

CERTIFICATE

This is to certify that the work contained in this M. Tech. Thesis titled "Study of the Dynamic Response of Organic Light Emitting Diodes and Crosstalk in Passive Matrix Displays" by Major Sanjay Mehrotra (Roll No. Y010438) has been done under my supervision and that this work has not been submitted elsewhere for the award of a degree.

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January 2002 | Major Sanjay Mehrotra

ABSTRACT

Displays are found today in thousands of products from wrist watches and cellular telephones to notebook computers and TV's, they are also a key component in the plethora of emerging communication and computing products. Thin, flat panel displays (FPDs) meet most of the present day requirements. As of now liquid crystal displays (LCDs) have the major market share of FPDs. But LCD's have limitation of viewing angle, operating temperature range, backlighting, higher power consumption and are heavy as well as fragile. Displays based on organic light emitting diodes (OLEDs) have made significant progress in the last decade and are poised to capture major chunk of the FPD market in the next few years. This is because OLED displays do not suffer from any drawback of LCDs and are far more efficient. The organic based display technology uses two types of matrix arrays. The "passive matrix" and the "active matrix". The passive matrix display technology is simpler but suffers from some problems such as crosstalk. Active matrix on the other hand is much more efficient but is more expensive as compared to passive matrix.

The present work describes a detailed study of crosstalk in passive matrix OLED displays. For this study, initially a SPICE model of the OLED has been developed, the I-V characteristics of which match the experimental data. To identify the reasons for crosstalk in passive matrix, dynamic response of an OLED alone, and in passive matrix of different sizes has been studied by means of simulations. Study of DC as well as dynamic mode of operation of passive matrix under different conditions of row scanning and data input to columns has been studied. Comparison of errors in actual pixel outputs has been done for DC and dynamic cases. Flow of currents through different pixels and their elements under different conditions have been studied to identify reasons for crosstalk. A modified pixel model has been developed which eliminates crosstalk almost completely and offers far better response time.

The armed forces use a wide range of electronic equipment, some of which do not require very large size displays. The basic requirement is of displays which are portable, rugged, fast, consume less power and cost-effective. Passive matrix OLED displays meet these requirements to a large extent. Especially, roll-on (flexible) displays will be of great utility in the armed forces.

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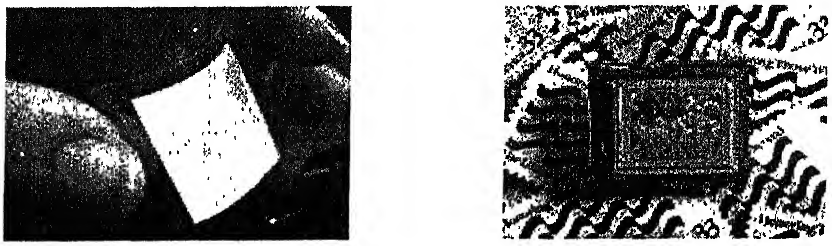
CHAPTER 1

An Introduction to OLEDs and OLED Displays

1.1 Introduction

The invention of the germanium transistor in 1947 marked the birth of modern microelectronics, a revolution that has profoundly influenced our current way of life. Nowadays single-crystalline silicon is the most widely used material in microelectronics. However, over the past two decades, an exciting, new flat panel display technology based on emission from thin layers of small organic molecules (Organic Light Emitting Diodes or OLEDs) or conducting polymers (Polymer Light Emitting Diodes or PLEDs) has emerged.

Organic semiconductor devices have made significant progress in the last several years and are now being proposed as replacements for conventional semiconductor devices in a variety of areas including thin film transistors (TFTs), memories, photodiodes, solar cells, and light emitting devices (LED's) for full-color flat panel displays. The organic materials used in these applications are light weight, flexible, conformable and are produced by simple manufacturing technologies, all of which make them potentially very inexpensive compared to inorganic semiconductor materials. Also, unlike inorganic semiconductors, for organic semiconductors there is no need to grow crystals, saw it, polish it, dope it, etc. It is processable in air, not in a chip-oriented processing environment. Organic semiconductor devices are potentially very inexpensive, can be fabricated with



(a) (b)

Figure 1.1 Small OLED displays
(a) shows flexible display (b) shows full colour display

low temperature processing, and are a molecular engineering approach to electronics and optoelectronics.

Compared to other display technologies available presently such as inorganic displays and Liquid Crystal Displays (LCDs), this technology offers thinner, lighter, brighter, higher contrast displays with lower power consumption, and response times fast enough for video applications. Whereas light emission from the present days displays such as LCD displays is Lambertian, organic displays exhibit a much wider viewing angle. In addition, because the small molecule emitter films are generally amorphous or polycrystalline with fairly good mechanical properties, there exists the possibility for flexible OLEDs or PLEDs fabricated by roll-to-roll coating. Some attractive features of OLED displays are listed below:

- Thin solid films with self-luminous emission layers.
- Low forward drive voltage (under 10V).
- High emission efficiencies, which result in high brightness in combination with low power consumption.
- Wide viewing angles (>160°).
- Fast response times (<10μs).
- Thin and lightweight display construction.
- Emission wavelengths tunable by incorporation of suitable fluorescent dyes in the emissive layers.
- Potential for low cost manufacturing.
- Low temperature processing technology and compatible with flexible substrate displays.
- Environment friendly features such as:
  - Reduction in power consumption.
  - OLED displays do not use mercury, which contains backlight assemblies.

The fact that they are organic materials means that they are abundant and are relatively inexpensive. Some organic materials such as a class of π -conjugated polymers, pentacene, thiophene oligomers such as α-hexathinylene (α-6T) have semiconductors properties in the neutral state and high electronic conductivity in the partially oxidized state. However, the advantage of simplicity must be weighed against the inferiority of the electronic properties of current semiconducting organic materials compared to the inorganic semiconductors. Currently, there is much work in developing a thorough understanding of the molecular, microscopic, and macroscopic properties of organic semiconductors. With this understanding, improved electrical or optical properties can be achieved by chemical modifications.

Currently, more than 70 companies worldwide such as Kodak, Pioneer Corporation, Sanyo and Ritek to name a few are developing display technologies based on OLED structures. Sales of displays based on OLEDs-such as car radios, mobile phones, digital cameras, camcorders, PDAs, games, and subnotebook PCs are increasing and are forecast to grow to more than $1 billion in 2005, according to a Stanford Resources study.

1.1.1 Background and History

The first GaAsP LEDs were introduced in 1962 and it was around this time that electroluminescence (EL) was first reported in organic materials from experiments using both solid and liquid contacts to crystalline emitters as well as liquid emitters with solid contacts. Single crystals of anthracene were used as the emitting layer. These devices exhibited reasonable quantum efficiencies, but extremely high driving voltages (>50V). However, fabrication and packaging problems and short lifetimes hampered development of display products. In 1987, Tang and Van Slyke reported efficient and low voltage organic EL from a p-n heterostructure device, consisting of n-type aluminum chelate tris(8-hydroxy quinoline aluminum) (Alq_3), which served as the electron transport and emitting layer, and indium-tin-oxide (ITO) hole injection contact, and a $Mg_{0.9}Ag_{0.1}$ cathode.

Since then, numerous companies and universities around the world have developed new materials and device structures for OLEDs, which have resulted in further improvements in device colour saturation, efficiencies and lifetimes.

1.1.2 Device Structure and Operation

The basic device configuration for OLEDs is shown in figures 1.2 and 1.3 below: -

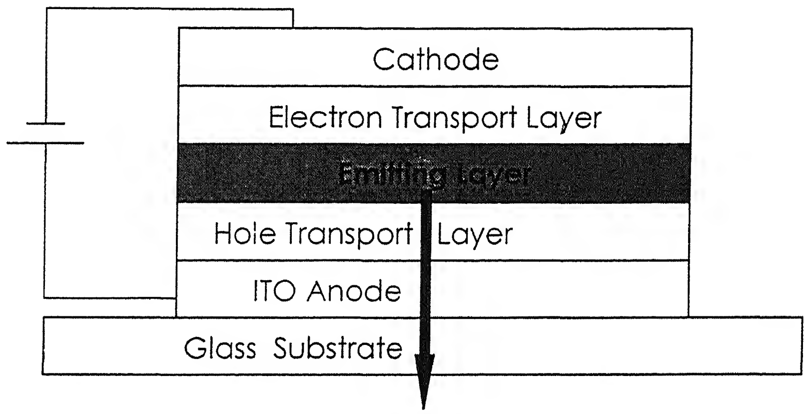


Figure 1.2 Device Structures of OLEDs.

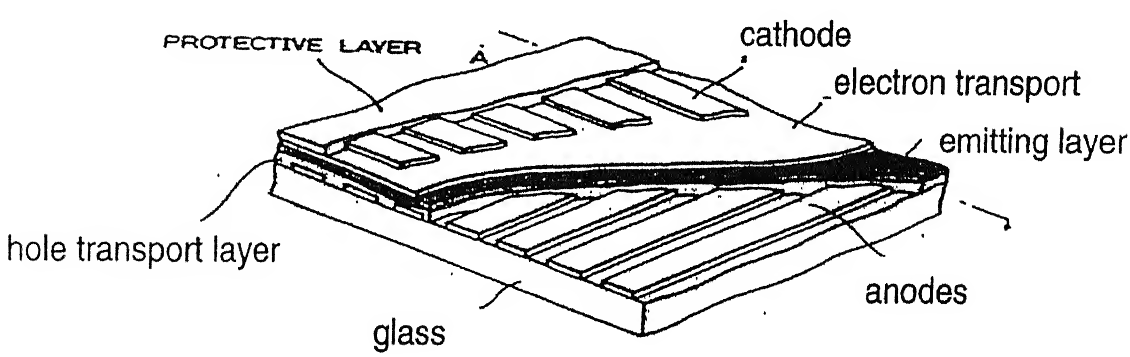


Figure 1.3 Basic Structure of OLED displays.

The configuration is basically a multilayered or 'sandwich' type structure consisting of a glass substrate, transparent anode, metal cathode, and two or more organic layers with different charge transport or luminance characteristics 300-1000A° in thickness. The morphology of organic layers typically ranges from semicrystalline to amorphous. Unlike inorganic LEDs, there are no lattice matching requirements with OLEDs, which greatly widens the types of substrates that can be used and the types of materials that can be combined together into devices. Use of multiple organic layers in the device geometry facilitates charge injection at the organic-electrode interface, leading to lower driving voltages. In addition, use of multiple organic layers allows the buildup of electrons and holes (and therefore, the location of the emission zone) to occur away from the electrodes, which significantly improves the efficiency of the device.

The thin layers of small organic molecules are incorporated into devices via physical evaporation at low ($<10^{-5}$ torr) pressures. The overall device structure typically consists of an ITO anode, ITO passivation layer, hole transport layer, emissive layer (which is usually doped), electron transport layer, and cathode. There are however variations to this basic structure such as Transparent OLED (TOLED) or Organic Inverted LEDs (OILEDs). The TOLEDs emit light from both bottom and top device surfaces. In OILEDs the cathode forms the bottom contact instead of the anode as in conventional OLEDs, as display in drivers which employ n-channel FETs it is desirable that the bottom contact be cathode.

As with inorganic LEDs, the device is conductive in forward bias, non-conductive in reverse bias (or rectifying), and the impedance drops with increasing voltage above the onset of light emission. The current transport follows a trap charge limited (manifested as power law relationship between voltage and current) at typical display operating points, and eventually becomes space charge limited at very high voltages (or current

densities). Typical operating voltages are 2-10V, depending upon the layer thicknesses and cathode materials used. Light output is proportional to the current flow in these devices, and there is virtually no delay between current flow and generation of light output, which is important for video applications. Moreover, the dynamic range of the light/current/voltage characteristics spans many orders of magnitude, and results in superior contrast ratio between ON and OFF states.

1.1.3 Materials

The desired characteristics of materials used in OLEDs include high luminescence efficiencies, adequate conductivities, good oxidative stabilities, good radical cation/anion stabilities, good temperature stabilities, good film forming properties, good colour saturation and purity, with a narrow emission spectrum and correct CIE coordinates. The characteristics of the anode and cathode materials used in OLEDs have a significant impact on device performance. The materials used are typically amorphous or semi-crystalline films. The typical p-type materials used are derivatives of triaryl amines, and n-type materials include derivatives of metal chelates, triazoles, and oxadiazoles. Alq_3 is commonly used as electron transport layer (ETL), whereas napthyl-substituted benzidine derivative (NPB) or biphenyl-diamine derivative (TPD) are generally used as hole transport layers (HTL). CuPc is commonly used as hole injection layer (HIL) and is deposited on top of transparent ITO anode.

Material selection is generally determined by the ionization potentials (for the anode) and electron affinities (for the cathode) of the organic materials used at the electrode/organic interface, which are typically in the range of 4.8-6eV and 2.5-3eV, respectively. Indium-tin-oxide (ITO) is generally used for the device anode, because of the high work function (Φ~5eV) and good transparency of the material in the visible spectrum. For the device cathode, low work function metals such as magnesium (Mg)-stabilized with 10% silver (Ag), calcium or lithium are used.

Though these metals are fairly reactive, encapsulation of the device is required in order to exclude water and oxygen after fabrication.

1.1.4 Device Efficiency and Stability

As it has been mentioned earlier that even though electroluminescence (EL) was observed in organic materials around the same time as discovery of inorganic LEDs however due to problems such as short lifetimes, poor efficiency and stability development of organic display products was hampered. Rapid progress has since been made in the areas of device efficiency and stability. This has been mainly due to improvements in materials and device design, as well as greater understanding of device degradation processes. One of the initial challenges for improving OLED performance was elimination of 'dark spot defect' formation during device storage and operation. This problem manifests itself as circular areas on the device that do not emit light and grow in size with time, independent of whether or not the device is operated. Dark spot defects have been found to be highly moisture sensitive, and are believed to be a result of cathode corrosion, either caused by improper exclusion of water during device fabrication, or to particulate defects in the cathode that allow moisture to penetrate into the cathode/organic interface. Therefore, device fabrication must be performed under rigorous exclusion of water, and the devices must be encapsulated to prevent the interaction of moisture with the device after fabrication. A second source of device instability is degradation of the organic material both physically and chemically.

1.1.5 Photometry

Luminous flux measured in lumens (lm) is the total luminous power emitted from a source. The lumen is the power-like unit of brightness-sensation-producing ability. Luminous intensity is defined as the total number of lumens from a source emitted in a given direction. The unit of luminous intensity is therefore lumens/steradian (lm/sr), which has been

renamed the candela (cd). The luminance of a specific segment of a source in a specific direction is defined as the luminous intensity emitted from that segment divided by the area of the segment's projection in that direction. The SI unit of luminance is cd/m^2. This is directly related to the human sensation of brightness.

1.1.6 Addressing Schemes for Displays

A display is an array of independently controllable pixels, the number of which depends on its dimension and resolution required by a particular application. Very large pixel counts are encountered in high-information content displays. For example, an NTSC standard TV screen requires 1.5×10^5 pixels. The addressing of a large number of pixels in an array is an important issue in the display technology. Direct addressing and Matrix addressing are suitable for OLED based displays. The direct addressing scheme, where each pixel is connected to an individual driver, can only be used for discrete indicators and simple alphanumeric displays with few characters. In this case, character patterns can be realized using shadow masks. By comparison, inorganic LED alphanumeric displays are expensive to fabricate because of the many individual diodes required to make up a single character, each with its own contacts and leads.

In a matrix addressed display, pixels are organized in rows and columns, and each pixel is electrically connected between one row lead, and one column lead. The addressing schemes where active electronic components are added to the pixels are called Active Matrix (AM) addressing; while those without extra active components in the pixels are termed as Passive Matrix (PM) addressing. Matrix addressed OLED arrays can enable the realization of high-information content, large area Flat Panel Displays (FPDs).

1.1.7 Passive Matrix OLED Displays

A passive display is formed by providing an array of pixels connected by intersecting anode and cathode conductors as shown in figure 1.4 below:-

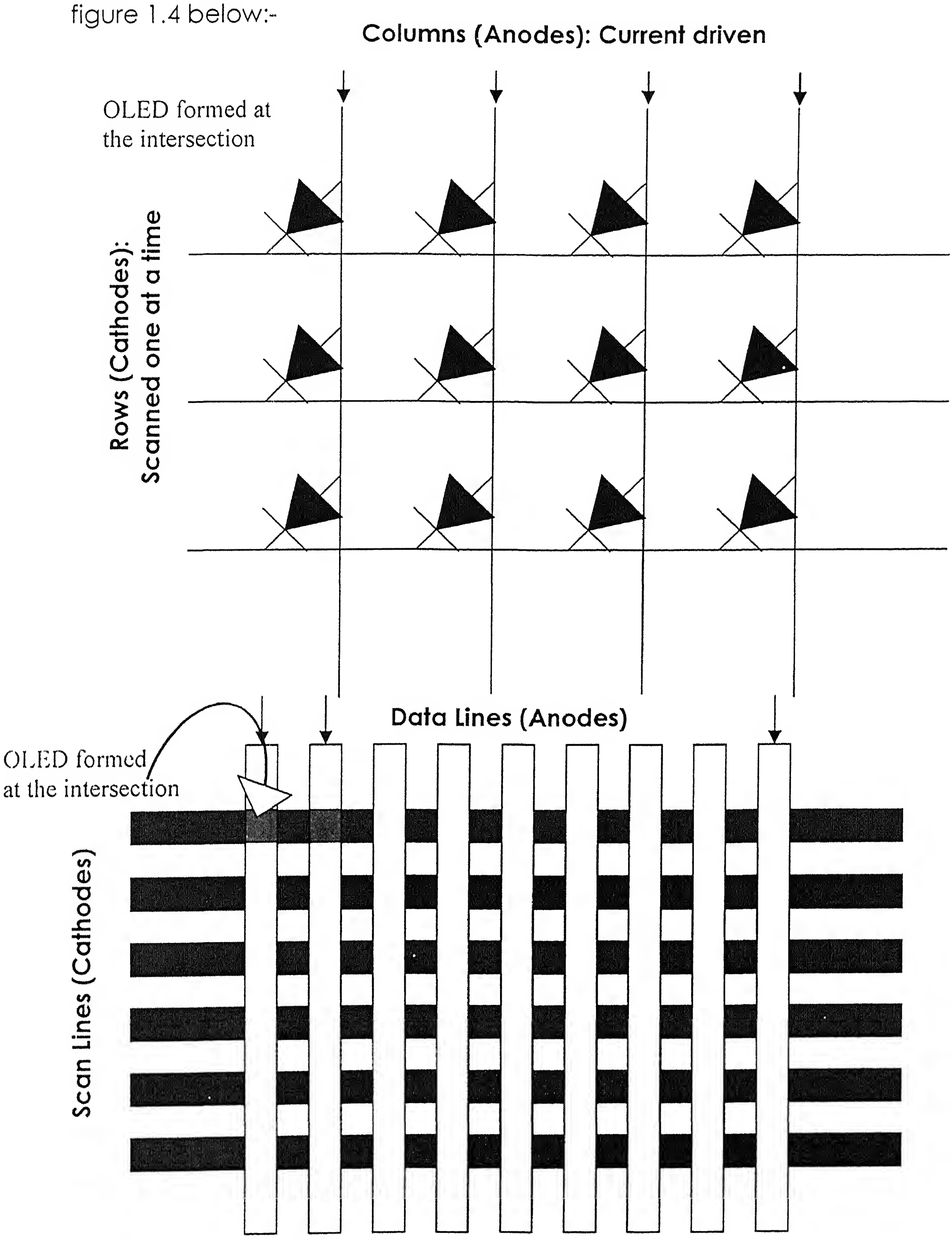


Figure 1.4 Basic design of OLED Passive Matrix displays.

In case of OLED passive matrix displays, a relatively simple but unique fabrication method is used. This method takes advantage of the line-of-sight deposition properties of vacuum deposited thin films. Here, a "base and pillar" structure is performed on patterned ITO anode lines. As the organic materials and cathode metal are deposited, the "base and pillar" structure automatically produces an OLED display panel with the desired electrical isolation for the cathode lines.

To drive a passive matrix display, electrical current is passed through selected pixels by applying a voltage to the corresponding columns from current drivers attached to the columns. Data signal is generally supplied to the column lines and synchronized to the scanning of the row lines. When a particular row is selected (grounded) the column data lines decide as to which pixels (OLED) are lit. A video output is thus displayed on the panel by scanning through all the rows successively in a frame time, typically 1/60-second. In order to have average brightness that are sufficient for display viewability, the passive matrix display operating point is, therefore, characterized by high peak current densities and low duty cycles, which results in additional mechanisms of instability, perhaps caused by localized, instantaneous heating processes within the device structure.

Passive matrix OLED displays have been commercialized in cellular phone applications and car audio system applications. Two companies, Pioneer Electronics and TDK, are mass-producing monochrome/colour OLED displays currently. Some of the key technical problems such as leakage currents, crosstalk and display stability are being solved at various levels.

1.1.8 Active Matrix OLED Displays

In the active matrix addressing scheme, an electronic switch is placed at each pixel, providing the means to retain video information on a storage capacitor during a complete a frame time. In case of active OLED displays, an additional active component is needed to provide the OLED drive current at each pixel. These active components can be field-effect transistors (FETs), such as crystalline silicon (Si) metal-oxide-semiconductor field-effect transistors (MOSFETs) or thin-film transistors (TFT's), depending on the application. Here, the channel material for TFT's may be polycrystalline CdSe or Si of various crystallinity ranging from polycrystalline Si (poly-Si) to amorphous Si (a-Si). Poly-Si and a-Si TFT's have been used in active matrix liquid crystal displays (AMLCDs), while CdSe TFT's are seldom used due to fundamental problems such as difficulties to deposit stoichiometric thin films, and lack of a highly insulating native oxide.

A pixel design for an AM OLED display using n-channel FET's is shown in figure 1.5 below.

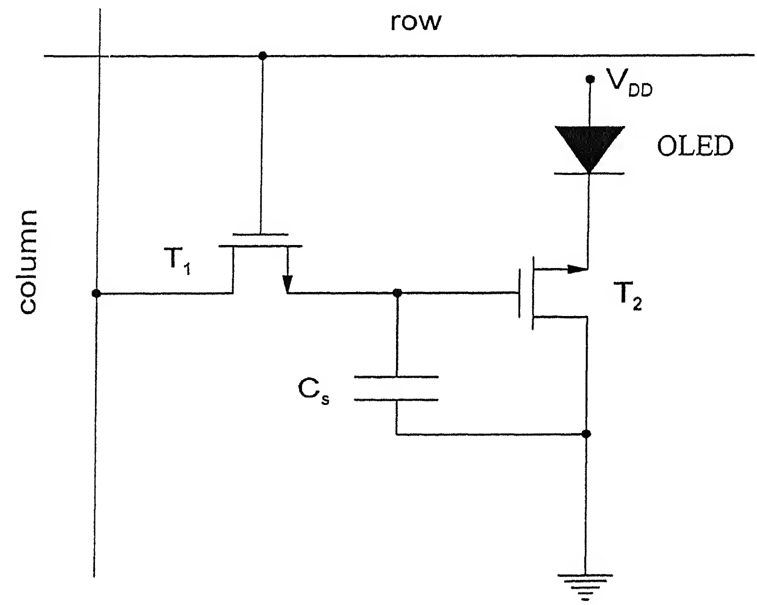


Figure 1.5 Pixel circuit design of AM OLED display using n-channel MOSFET

When a row is selected, the column signal is written via the accessing transistor T_1 to the gate of the drive transistor T_2 . The written voltage V_{G2} is therefore retained for a complete frame time T_f . Transistor T_2 operates in the saturation regime, where the OLED drive current I is controlled by the gate-to-source voltage V_{GS2} and has little dependence on the source-to-drain voltage V_{DS2}. The dc voltage source V_{DD} may be replaced with a pulsed voltage source to achieve ac operation, which has been shown [1] to improve OLED lifetime.

This particular design cannot be implemented using OLEDs deposited in a conventional sequence, since the metal cathode must be the first layer to be deposited on the TFT backplane. This problem is solved by using top emitting inverted OLEDs (OILEDs).

The pixel circuit can also be implemented with p-channel FET's as shown in figure 1.6 below.

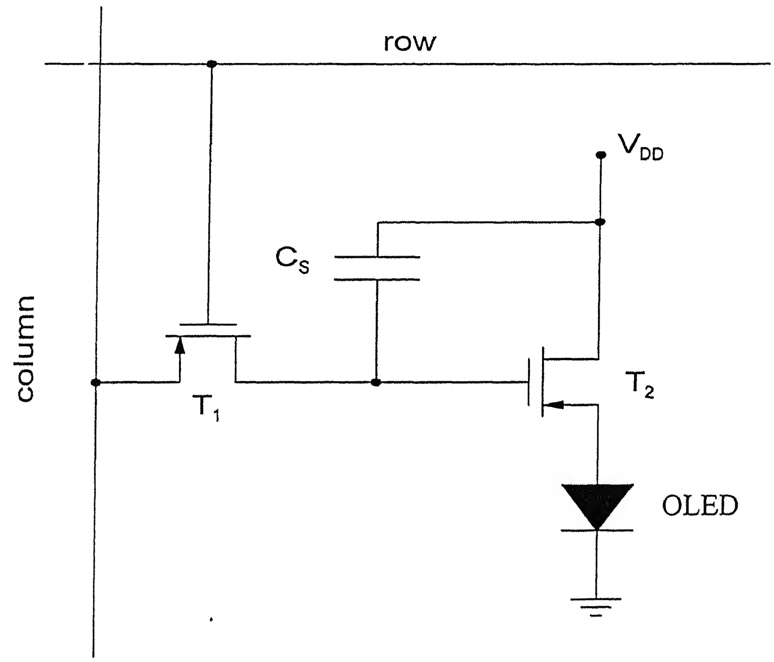


Figure 1.6 Pixel circuit design of AM OLED display using p-channel MOSFET

Although the pixel circuit using p-channel FETs eliminates the need for OILEDs, the performance of p-channel FETs is typically lower than that of n-channel FETs made from the same material. However, work on this aspect is under progress at a number of institutes the world over.

There are certain key advantages in AM OLEDs. These are listed below:-

- Low power consumption.
- High resolution.
- Large area.
- Robust pixel design.
- Integrated drivers.

In AM OLEDs as each individual pixel can be addressed independently via the associated TFT's and capacitors in the electronic backplane hence, in principle, each pixel element can be selected to remain ON during the entire frame time. Therefore, there are no limitations to the pixel count, resolution, or size of display. Furthermore, current drivers for OLEDs and the necessary scanning circuitry can be built directly on the substrate, thus eliminating the need for high density interconnects and discrete peripheral devices.

However, the circuitry, and as a result the fabrication of AM OLEDs is much more complex as compared to that of PM OLEDs and hence for smaller displays PM OLEDs will prove to be more suitable and cost effective if problems such as current leakage and crosstalk are overcome to some extent in these displays.

1.2 Scope of Thesis Work

The review of literature surveyed on OLEDs and OLED displays has revealed that most of the work in this field has been on study of DC behaviour of OLEDs and displays based on OLEDs. Not much work has been put in the study of the 'dynamic behaviour' of OLEDs and their displays. Also, problems such as current leakage, crosstalk and small size of passive matrix displays have not been given due importance, probably due to the advent of active matrix displays. However, as passive matrix have a simple structure and low cost it is felt that more efforts should be put in to improve the quality of passive matrix displays. Problems of passive matrix displays such as crosstalk and size limitation can be studied and reduced by adopting different techniques so that simple, low cost, high resolution and large size displays can be brought into practical use with passive matrix OLED technology.

In this work an effort has therefore been made to study the 'dynamic response' of OLED and reasons for crosstalk in passive matrix. For this, simulations of a single OLED and OLED within passive matrix of different sizes has been done to study both the DC and dynamic behaviour of OLEDs. Because, it is felt that a better understanding of the DC as well as dynamic behaviour of OLED and displays based on OLEDs would lead us to identifying the reasons for crosstalk and size limitation in case of passive organic matrix. Once the exact reasons could be identified then techniques can be developed to overcome these drawbacks.

1.3 Organization of Thesis Work

As the scope of the thesis is to study the 'dynamic response' of OLED and crosstalk in passive matrix OLED displays the thesis work has been organized as given in succeeding paragraphs.

1.3.1 Literature Survey

As the field of organic displays is fairly new proper books and texts are still not available on this topic. However, as this emerging display technology is expected to have a very bright and promising future and is poised to grow to more than $1 billion by 2005 a large number of universities, institutes and companies the world over are working on devices and technologies to develop improved and cheaper OLED displays.

To start work on the thesis, literature on OLEDs and OLED displays published in a large number of technical journals has been surveyed to collect relevant data on this topic. Behaviour of OLEDs, their I-V characteristics, design methodology, device structure, materials used and also design and operation of display matrix have been studied.

1.3.2 OLED Model

The current-voltage (I-V) and current density-voltage (J-V) characteristics of OLEDs developed at different centers have been studied from the literature available in various technical journals [2], [3] and [4]. The I-V characteristic given in [2] has been selected for our OLED model. A SPICE (Simulation Program with Integrated Circuit Emphasis) model of OLED has been developed, J-V characteristics of which closely match with the experimental model given in [2].

1.3.3 Dynamic Response of OLED

The dynamic response of the OLED developed has been studied. Simulations using PSPICE (Microsim) have been done on a single OLED and study the dynamic response of an OLED within passive matrix displays of different sizes has been done.

1.3.4 Crosstalk in Passive Matrix

A passive matrix consisting of 1800 OLEDs arranged in 60 columns and 30 rows has been designed and SPICE simulations of this matrix have been done to study its response under different conditions so that reasons for crosstalk can be identified and solutions to overcome this problem can be developed in order to get a superior passive matrix which has significantly less crosstalk and better resolution.

1.3.5 Modified Passive Matrix

In order to overcome crosstalk in passive matrix and also to improve it's response time a 60x30 (60 columns and 30 rows) passive matrix in which each OLED has a poly-Si TFT in it's model has been designed. Simulations have been conducted on this passive matrix and it's response has been studied under different conditions.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The field of OLEDs and organic displays is fairly new. It was only in 1987 that electroluminescence was first reported from an organic p-n structure device. Due to this reason not much text is available on this topic yet. Therefore, at the start of this work and subsequently, literature on OLEDs and their displays has been searched from a large number of technical journals. A detailed study of the work done on this topic so far, and on current research, has been carried out. As this display technology is fast emerging to replace the present day LCD technology a lot of work has been done in this field and is currently in progress in the universities at Cambridge, California, Princeton and Shanghai, to name a few and also at some companies namely, Kodak, Sanyo, Pioneer Corporation, Ritek, Emagin and Uniax. A few papers on some pioneering work done in this field have been used as reference in this thesis work. A brief summary of the references drawn and their sources is given in succeeding paragraphs.

2.2 I-V Characteristics of OLED

An exhaustive study of the relationship between electroluminescence (EL) and current transport in organic heterojunction light emitting devices has been carried out by P.E. Burrows, et. al. [4]. The study has been carried out on a wide range of materials, temperatures and currents. They have found that I-V and EL characteristics of a vacuum deposited heterojunction OLED is consistent with the injection of charge into a thin film with a large density of traps distributed in energy beneath LUMO. Current in trap charge limited regime is determined by the bulk properties of the solid rather than contact effects. Increase in bias results in rapid increase in effective carrier mobility and therefore a rapid, power law

increase in current. At sufficiently high injection levels, all the traps are filled, and as a result current becomes space charge limited.

2.3 L-V Characteristics of OLED

In the tutorial on OLED displays [2] the luminescence vs voltage (L-V) characteristics of OLEDs have been discussed. The data has been obtained experimentally and it is shown that luminescence is directly proportional to drive current. The relationship that exists between instantaneous luminance and drive current density is as under:-

1mA/cm^2 (J): corresponds to 100cd/m^2 of instantaneous luminance.

This relationship has also been discussed at length in [1]. A SPICE model of OLED has been developed [3] in which a close match of experimental and simulation data has been obtained.

2.4 Design of Organic Passive Matrix

A systematic and quantitative analysis of the design of flat panel displays (FPDs) based on OLEDs has been done by G. Gu and S.R. Forrest [1]. They have estimated key performance parameters for OLED based displays; system issues, including addressing schemes and strategies required to achieve full colour displays. Limitation of size of passive matrix due to requirement of high drive currents and unintentional addressing of non-selected pixels in a passive matrix due to unintentional reverse biasing have been discussed in detail. Design of passive matrix has been discussed at length in [7] and [8]. Zhang Bu-xin, et. al. [7] have designed a 96x64 passive matrix. The scheme used by them for addressing rows and columns is unique. In this scheme, the non-selected columns are grounded and only one row is grounded at a time i.e. selected. The remaining rows are given a bias. The authors claim to have achieved an average display luminance of 100cd/m^2 without crosstalk, with this design. This addressing scheme has been tried out in this work.

2.5 Crosstalk in Passive Matrix

Several sources of DC crosstalk such as reverse leakage currents, low rectification ratio's of OLEDs and optical crosstalk have been discussed by D. Braun [9]. Study of crosstalk arising from electrode resistance, pixel leakage currents and location of faulty pixels is given in [10].

CHAPTER 3

Dynamic Response of OLEDs and Crosstalk in Organic Passive Matrix Displays

3.1 Dynamic Response of OLED

The structure of a conventional OLED [1] is shown in figure 1.2. Electrons and holes are correspondingly injected from the cathode and anode and migrate through the electron and hole transport layers. Electroluminescence is generated by radiative recombination of these carriers near the interface between the two transport layers.

For generation of electroluminescence the OLED device is driven by a constant current/ voltage. Two types of constant current operations are applied to the device: a direct current (DC) mode and an alternating current (AC)/ pulsed current mode. In the DC mode, which corresponds to the conventional direct current operation, the device is driven by a direct current and emits light continuously.

In the 'dynamic' mode of device operation, the device is driven by a pulsed constant current for the forward direction, and it emits pulsed light. However, while reverse voltage or no voltage is applied to the device, the device does not emit light. Van Slyke [6],[12] reported that the OLED driven by an AC mode has an improved stability compared with that of OLEDs driven by a DC mode.

3.1.1 I-V Characteristics of OLED

The device current vs voltage (I-V) characteristics, are well described in [4]. The I-V and electroluminescence (EL) characteristics of OLED's vary with types of materials, thicknesses of layers and temperature.

It is seen that the current is limited by a large density of traps with an exponential energy distribution below the lowest unoccupied molecular orbital (LUMO). The I-V characteristics of vacuum deposited hetero-junction OLED is consistent with a large density of traps distributed in energy beneath the LUMO. This model implies that trap charge limited (TCL) currents dominate transport in OLEDs at high injection current. Current in this TCL regime is determined by the bulk properties of solids rather than the contact effects. Increasing bias results in an increase in injected charge, thereby filling the limited number of traps. The reduction in empty traps results in rapid increase in effective carrier mobility, and therefore a rapid, power-law increase in current ($I \propto V^m$). At sufficiently high injection levels, all the traps are filled, and consequently current becomes space charge limited (SCL).

It can be summarized that at lower voltages ($V<V_{on}$), $I=V/R_e$, indicating ohmic behaviour; whereas at higher operating voltages ($V>V_{on}$), $I=kV^{m+1}$ with m~6-10, suggestive of trap limited conduction characteristics of small–molecule OLEDs [4]. Here, V_{on} is the turn-on voltage defined as the voltage at which currents due to ohmic and trap limited conduction [1] are equal; R_e is the effective resistance of OLED at low voltages; and k is the proportionality constant.

The OLED model as given in [2] has been used in the design of passive matrix in this work. The I-V characteristics of the OLED model used are brought out clearly in figure 3.1. These characteristics closely match the experimentally obtained characteristics [2]. As in this work OLEDs have been operated around 6V, hence the I-V and J-V characteristics have been taken for the range 0V-9V.

The size of each pixel in the passive matrix has been taken as 400μmx200μm. The current density vs. voltage (J-V) characteristics of the OLED model are given in figure 3.2.

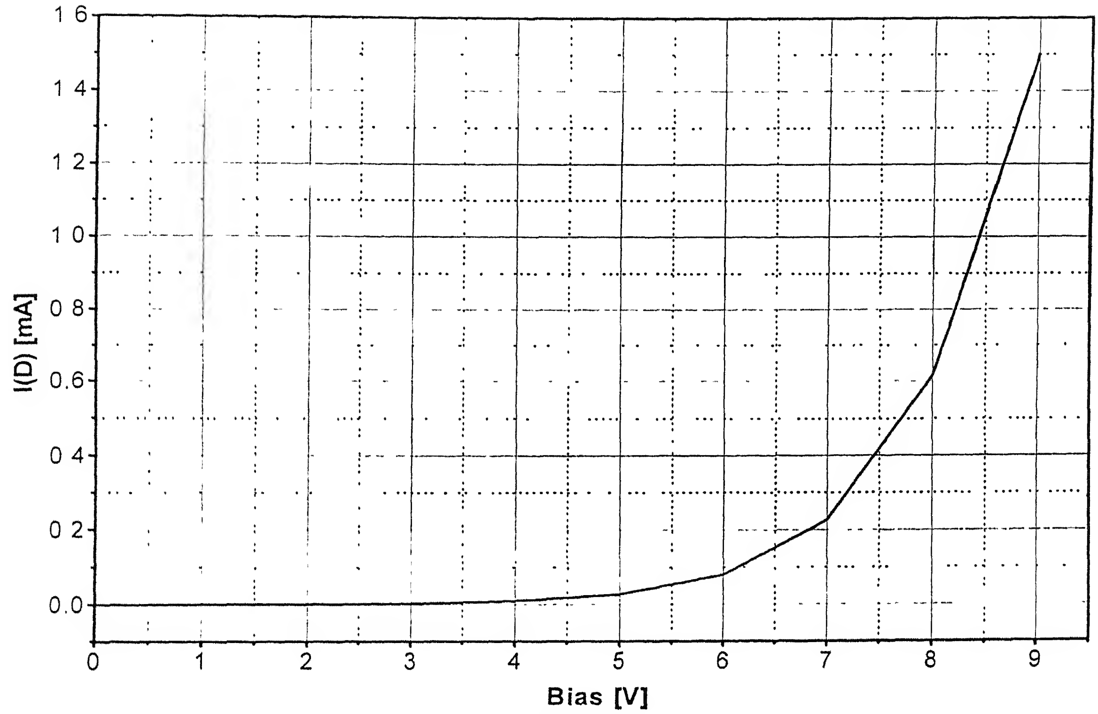


Figure 3.1 I-V Characteristics of OLED

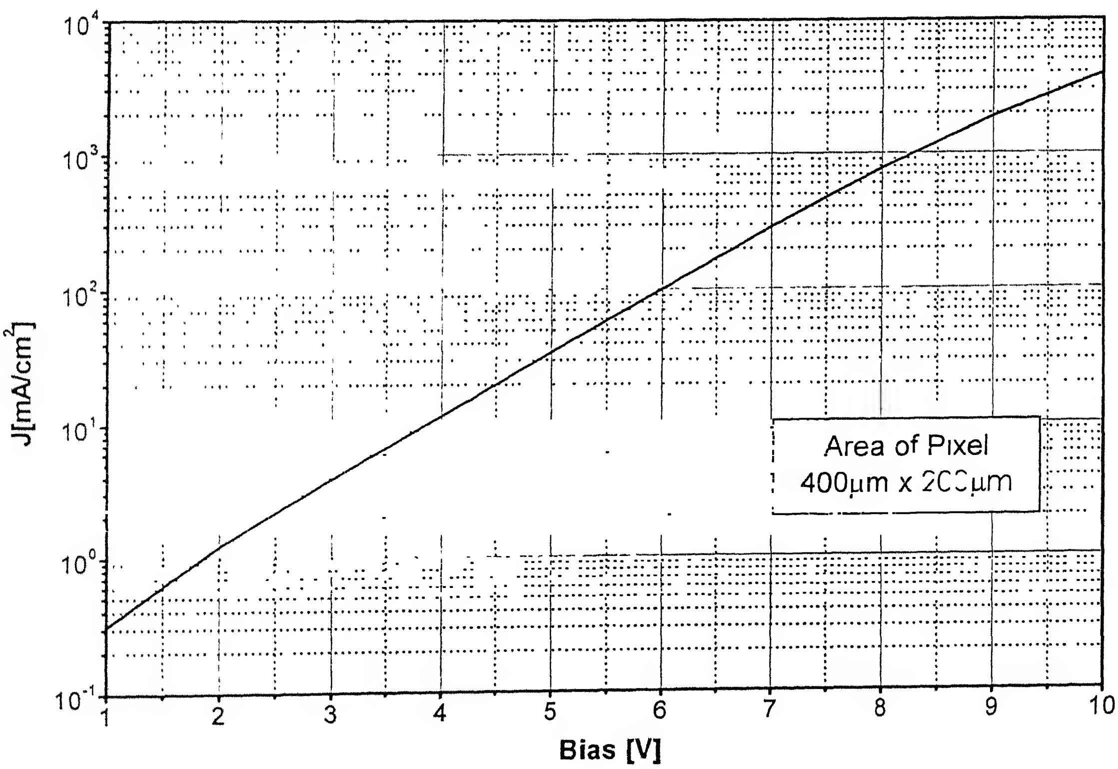


Figure 3.2 J-V Characteristics of OLED

3.1.2 SPICE Model of OLED

A SPICE model of OLED developed by J. P. Bender, et. al. [3] has been used with some modifications in this work. J-V characteristics of this modified OLED model obtained by means of SPICE simulations nearly match the experimental data of OLED given in [2].

For making a SPICE model of OLED following two options are available [3]. First, each individual layer in the OLED is modeled as a capacitor shunted by a series combination of a resistor and a diode as shown in figure 3.3. The capacitor represents the physical capacitance of the layers. The value of each capacitor is calculated from the thickness of the corresponding layer and the dielectric constant of the organic material. The resistor accounts for the fairly large bulk series resistance associated with an OLED layer; large series resistance is an inevitable consequence of employing materials with extremely low mobilities. The diode accounts for the rectifying nature of an individual OLED layer. An additional resistor is placed in series with the stack of modeled layers to account for the sheet resistance of the ITO anode and any external resistance. The multi-diode model was developed so that fit between simulation data and experimental data is optimal [3].

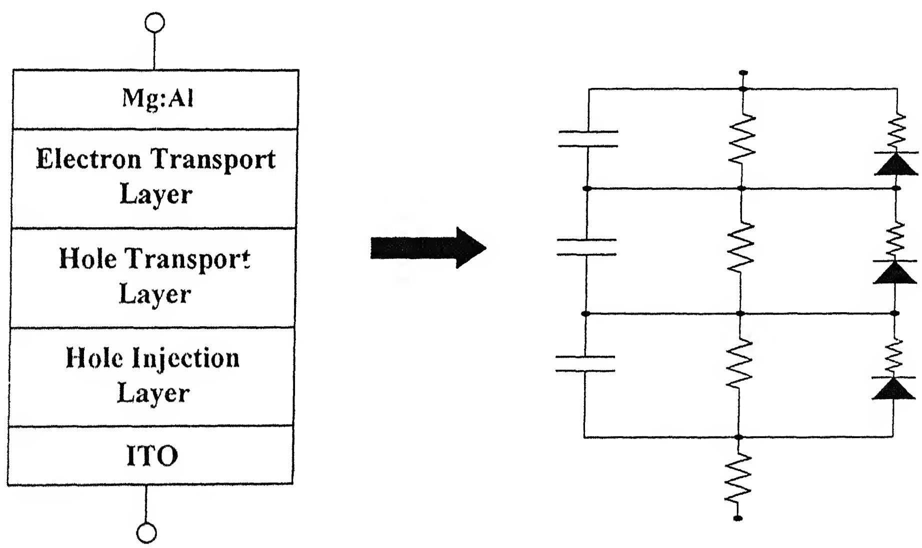


Figure 3.3 Multiple diode SPICE model

The second option is that a simpler model is able to approximate OLED behaviour as optimally as the multiple-diode model [3]. The simpler model typically consists of a capacitor shunted by a diode in series with a resistor. The diode now represents the total rectified current flow in an OLED, the capacitor is the total OLED stack capacitance, and the shunt resistor accounts for the total bulk resistance of all the OLED layers. Again, the parallel combination of the diode, the resistor and the capacitor is placed in series with a resistor, which accounts for the ITO sheet resistance. The parameters of different elements of the simple OLED model shown in figure 3.4 have been obtained as explained here.

Total OLED stack capacitance

$C = \epsilon A/z$ ....(I)

Where,

$\epsilon \approx 10^{-13}$ F/cm, is permittivity of the organic materials [1]

A, is the arèa of the pixel: taken as 400μm x 200μm

$z \approx 1000$A°, is the total thickness of the organic materials [1]

Bulk resistance of organic layers (R)

This value is obtained on matching J-V characteristics of this OLED model with that given in [2]. It is taken as 155Ω.

Resistance of ITO anode (R_{ITO})

Sheet resistance of ITO as given in the paper on flat panel displays by Gu and Forrest [1] is 20Ω/□.

As area of OLED is taken as 400μm x 200μm, therefore R_{ITO}=40Ω.

Diode parameters

I_S (saturation current)=130nA

N (ideality factor)=36

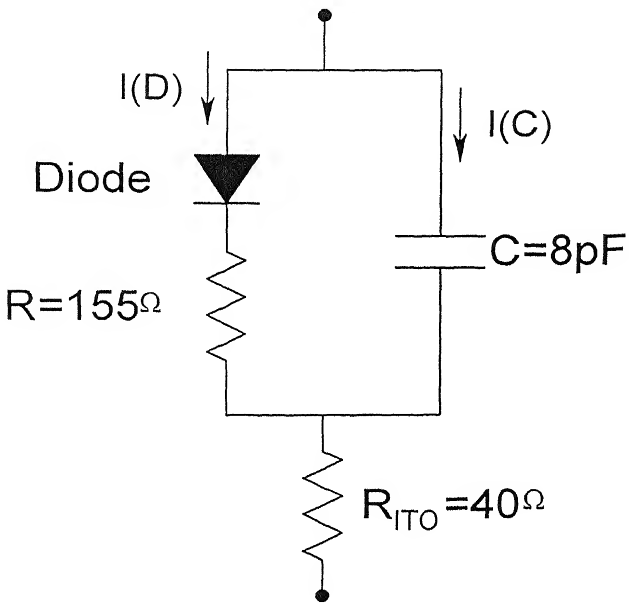


Figure 3.4 Single diode SPICE model

3.1.3 Study of the Dynamic Response of a Single OLED

The basic OLED model as shown in figure 3.4 has been used to study the dynamic response of an individual OLED. In this work 'Response Time' of the OLED is taken as the time required by the diode current, I(D) to reach 90% of it's steady state (max) value.

For this, the OLED is initially driven with a current pulse of 6μA with an ON time of 13μs and pulse period of 20μs as shown in figure 3.5(a). It is observed that the response time of the OLED in this case is approximately 7.5μs as seen in figure 3.6. The maximum voltage that develops across the diode is 3.588V.

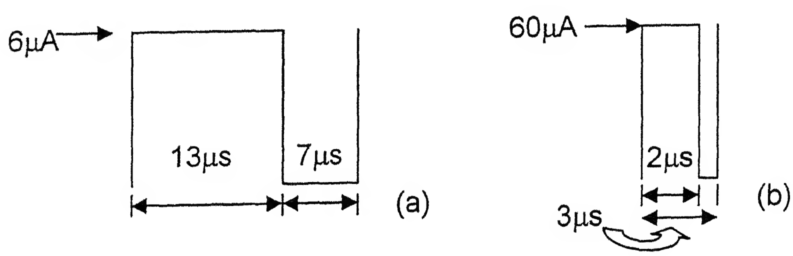


Figure 3.5
Current pulses

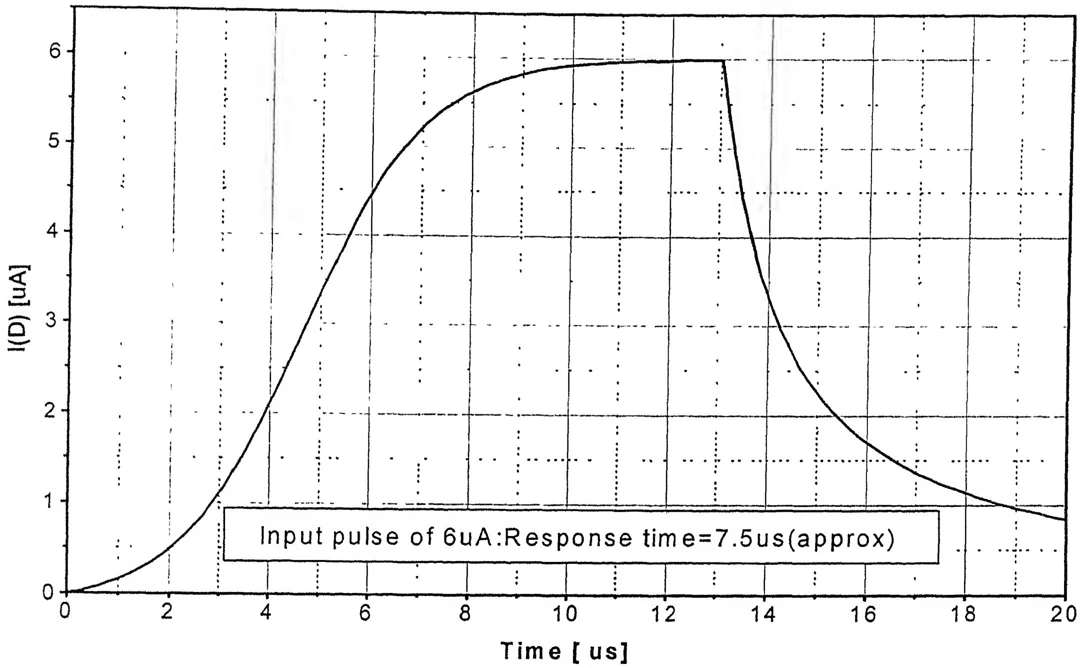


Figure 3.6 Response of single OLED when input pulse is of 6µA

In another case, the same OLED is driven by a current pulse of 60µA with ON time of 2µs and pulse period of 3µs as shown in figure 3.5(b). In this case the response of the OLED is approximately 1.1µs as is evident from figure 3.7. The maximum voltage (V_{max}) that develops across the diode in this case is 5.72V.

Therefore, it can be inferred that the response time of an OLED is inversely proportional to the magnitude of the current pulse. This can be explained with the help of the following relationship.

$$dt = C.dV/I \quad \text{...(2)}$$

here, C is fixed(8pF).

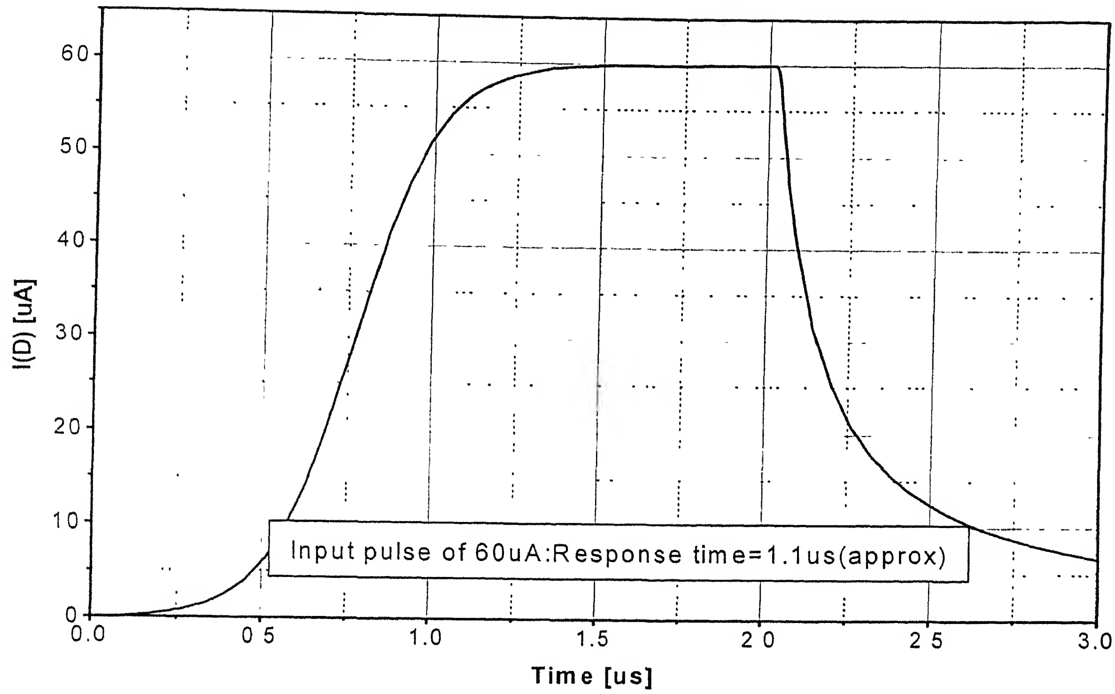


Figure 3.7 Response of single OLED when input pulse is of 60μA

3.1.4 Design of Passive Matrix

A passive matrix OLED (PM OLED) array consists of two sets of electrically isolated leads (rows and columns) arranged orthogonally with an OLED at each intersection, as shown in figure 1.4. Column and row drivers are employed to address columns and rows depending upon the pixels to be lit. To achieve gray levels, the column drivers must be current sources since the pixel luminance is proportional to the drive current, and the I-V characteristics of the OLEDs are highly non-linear [1] as discussed in section 3.1.1.

Such a monochromatic, PM OLED display prototype has been demonstrated [1]. Here, we quantitatively study an N (columns) x M (rows) PM array of identical OLED pixels, with W_r wide rows separated with gaps of width D_r, and W_c wide columns separated by gaps of width D_c. The aperture ratio (r_a) of this display is therefore:-

$R_a = W_r.W_c/[(W_r+D_r).(W_c+D_c)]$ ....(3)

The parameters/values of different elements used in the design of the passive matrix are as given below:-

- Pixel size=400μm x 200μm

  W_r=400μm, D_r=139μm, W_c=200μm, D_c=78.5μm

  ∴r_a=0.52 (from equation 3).

- Row resistance

  Sheet resistance of Mg/Al cathode=0.03Ω/□ [1]

  ∴resistance of row element between two adjacent pixels =(0.03Ω/□ x 78.5μm)/400μm ≈0.006Ω.

- Column resistance

  Sheet resistance of ITO anode=20Ω/□ [1]

  ∴resistance of column element between two adjacent pixels=(20Ω/□ x 139μm)/200μm ≈14.5Ω.

Using these elements and OLED, passive matrix of different sizes have been designed. A basic design of the passive matrix, which has been used in this work, is given in figure 3.8.

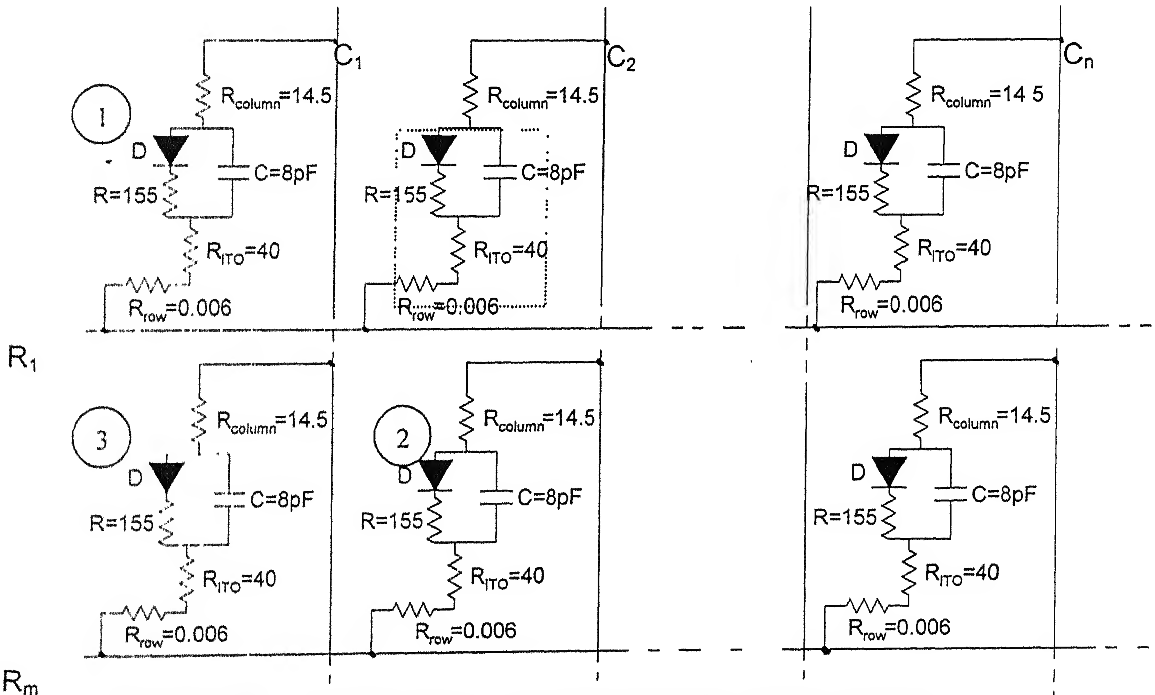


Figure 3.8 An 'N' column and 'M' row OLED Passive Matrix

In figure 3.8, C_1, C_2, C_n are the first, second and N^{th} columns, respectively. Whereas, R_1 and R_m are the first and the M^{th} rows, respectively. If second column C_2 is driven by a current pulse and first row R_1 is grounded simultaneously, then the pixel at the intersection of C_2 and R_1 will glow. Such a pixel which is lit by driving of corresponding row and column has been referred to as 'Selected Pixel' in this work, for sake of convenience. In figure 3.8 the selected pixel is therefore the one at the intersection of C_2 and R_1 The selected pixel has been enclosed in a rectangle in the figure for ease of identification. The other pixels on the column which is driven by a current pulse or is selected (C_2 in this case), other than the selected pixel are referred to as 'Column-selected pixels'-one of these is marked '2' in the figure. All the pixels on the row, which is being scanned i.e. the selected row (R_1 in this case), except for the selected pixel itself, are called 'Row-selected pixels'-one of these is marked '1' in the figure. All the remaining pixels in the matrix are referred to as 'Non-selected pixels'. In figure 3.8 the pixel marked '3' is one of the non-selected pixels.

3.1.5 Drive Currents

An important issue in the functioning and performance of OLED passive matrix is the driving of pixels with optimum current pulse, for optimal duration so that sufficiently high voltage does not develop across OLEDs which may damage them and on the other hand desired luminance is obtained. It is seen that unintentional direct coupling occurs when pixels in different rows are simultaneously addressed. Hence, a number of factors have been considered.

An addressed (selected) pixel must be driven with a pulsed current at a duty cycle, d, to avoid catastrophic, irreversible breakdown (or shorting) caused by long term reverse bias on the non-selected pixels [1]. To achieve an average display luminance of L_d, the pixel must therefore be driven to an instantaneous luminance of:

$$L(0) = \frac{M.L_d}{\eta .d} \quad \text{.............................(4)}$$

This requirement, which may limit the number of rows in a display, must be considered in the design. Besides limiting the number of rows, the high instantaneous current requirement also lowers the OLED power conversion efficiency by increasing the drive voltage.

In this work, the largest size of the passive matrix used for doing simulations is a 60x30 (60 columns and 30 rows) matrix. The size is limited to 60x30 due to constraint of the simulation software (pSPICE-Microsim) used. However, for determining the duty cycles of the current pulses a matrix with 480 rows has been considered. The maximum drive current value and duty cycle of current pulse used for simulations has been explained as under.

- Duty Cycle

  As given in [2], the rate of 60 frames per second is taken for determining the duty cycle required for the drive current pulses. This frame rate is considered quite optimum for viewing of video information by humans. For a matrix of 480 rows, time required for scanning of one row is 34.72μs (34.72μsx60x480=1 frame time). This time period of 34.72μs is divided into an ON time of 30μs and OFF time of 4.72μs to get a duty cycle of 0.86. It is clear from equation (4) that higher the value of 'd' lower is the drive current required.

- Magnitude of Current Pulse.

  It is learnt from the literature collected on the topic [1], [2] that an average luminance (L_d) of approximately 100 cd/m^2 is required to obtain good brightness, and an average luminance of 15 cd/m^2 is good enough to get sufficient low level brightness. Hence, the instantaneous luminance, L(0) required for driving a matrix of 30 rows to L_d of 100 cd/m^2 when d=0.86 and r_a=0.53 is calculated using equation (4) and is found to be 6.58x10^3 cd/m^2. The corresponding current density for this L(0) is obtained from the current density vs luminance (J-L) figure given in [2]. From the value of J thus obtained,

drive current (I) is found out to be 60μA (approximately). Similarly, for an average luminance of approximately 15 cd/m^2 the drive current required is approximately 6μA. Hence, in this work the drive current range of 6μA to 60μA has been used to obtain a gray scale for simulations.

3.1.6 Response of an OLED in Passive Matrix

In section 3.1.3 the response of a single OLED in case of drive current pulses of 6μA and 60μA has already been studied. In this section study of the response of a single OLED in organic passive matrix of different sizes has been undertaken. Response of an OLED has been studied in a 4x3 (4columns and 3 rows), 30x15 and 60x30 passive matrix under different conditions. The different conditions (cases) for which response of an OLED in display panels has been simulated are listed below:-

- Case1: Input of 60μA to one column, remaining columns connected to a current source at 0A/open circuited. Selected row grounded and remaining rows open circuited.

  To study the effects of addressing schemes given in [7], mentioned at section 2.4, bias is applied to non-selected rows in cases 2 and 3.

- Case2: Input of 60μA to one column, remaining columns open circuited/connected to a current source at 0A. Selected row grounded and remaining rows at +5V.
- Case3: Input of 60μA to one column, remaining columns grounded. Selected row grounded and remaining rows at +5V.

The response of selected OLEDs in passive matrix of different sizes, for different cases under consideration are shown in figures 3.9 to 3.17. It is observed that the response time of the selected OLED increases with the size of the passive matrix in which it is used. It is also observed that the

response time varies for different cases considered in this work. For example, the response time is more in case1 as compared to cases 2 and 3. This means that more capacitive effect comes into play in case1 as compared to cases 2 and 3.

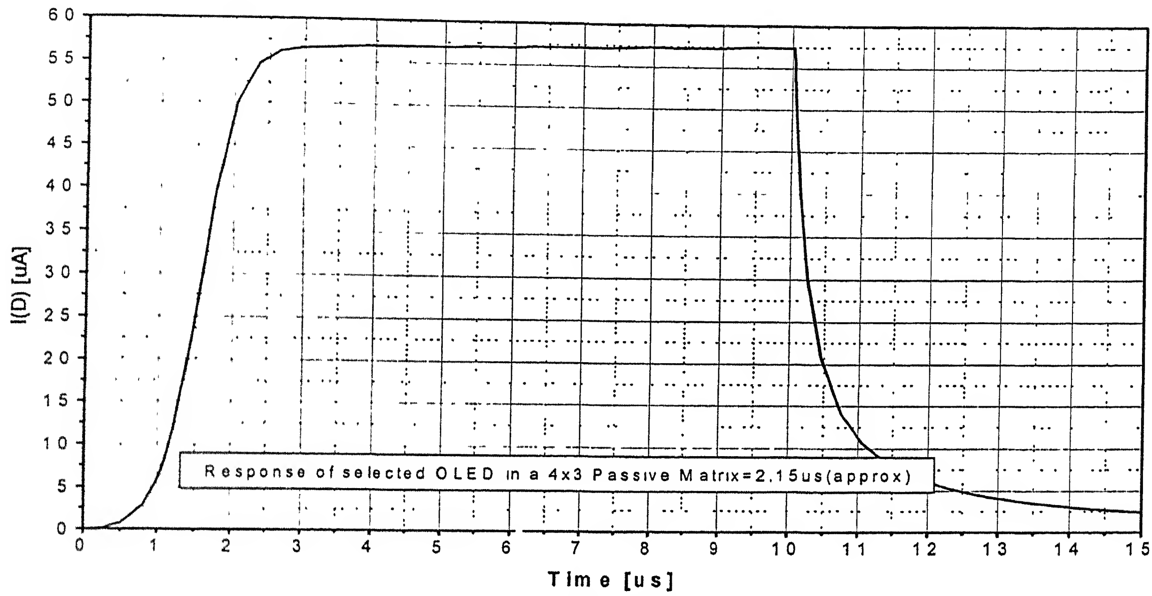


Figure 3.9 Response of the selected OLED in a 4 x 3 Passive Matrix (case1)

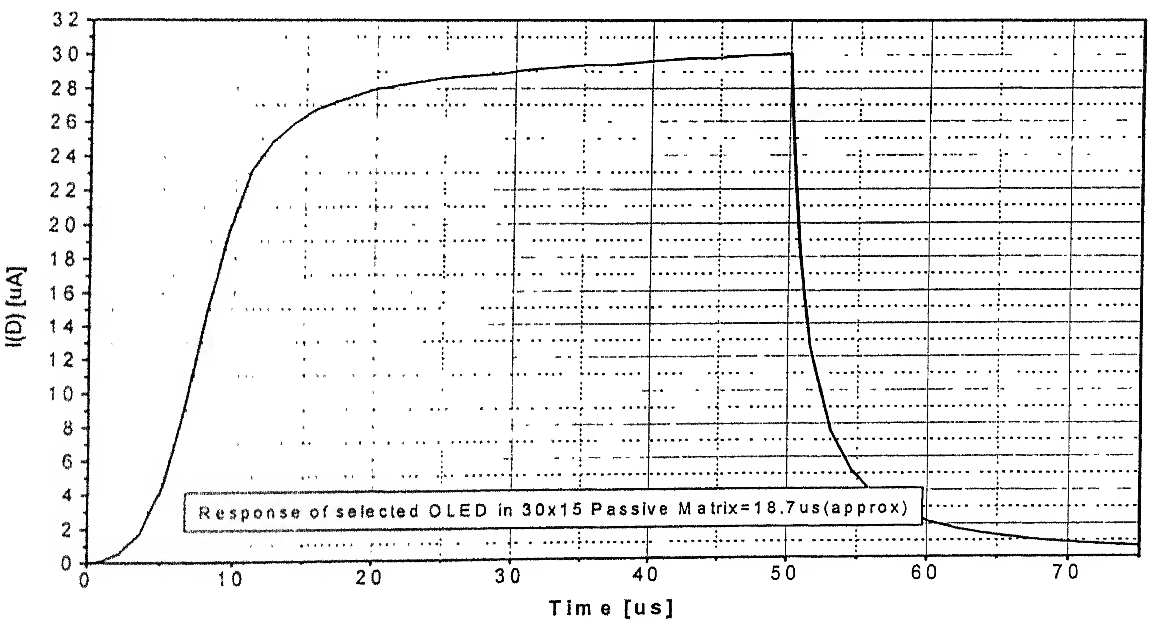


Figure 3.10 Response of the selected OLED in a 30x15 Passive Matrix (case1)

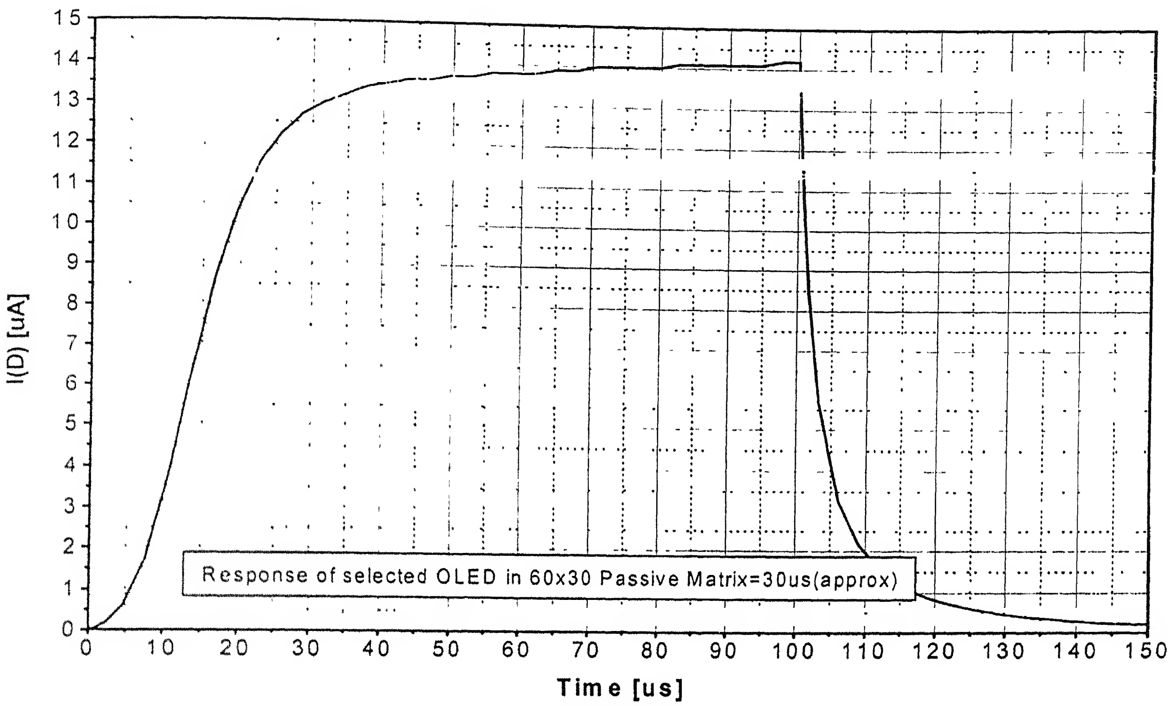


Figure 3.11 Response of the selected OLED in a 60x30 Passive Matrix (case1)

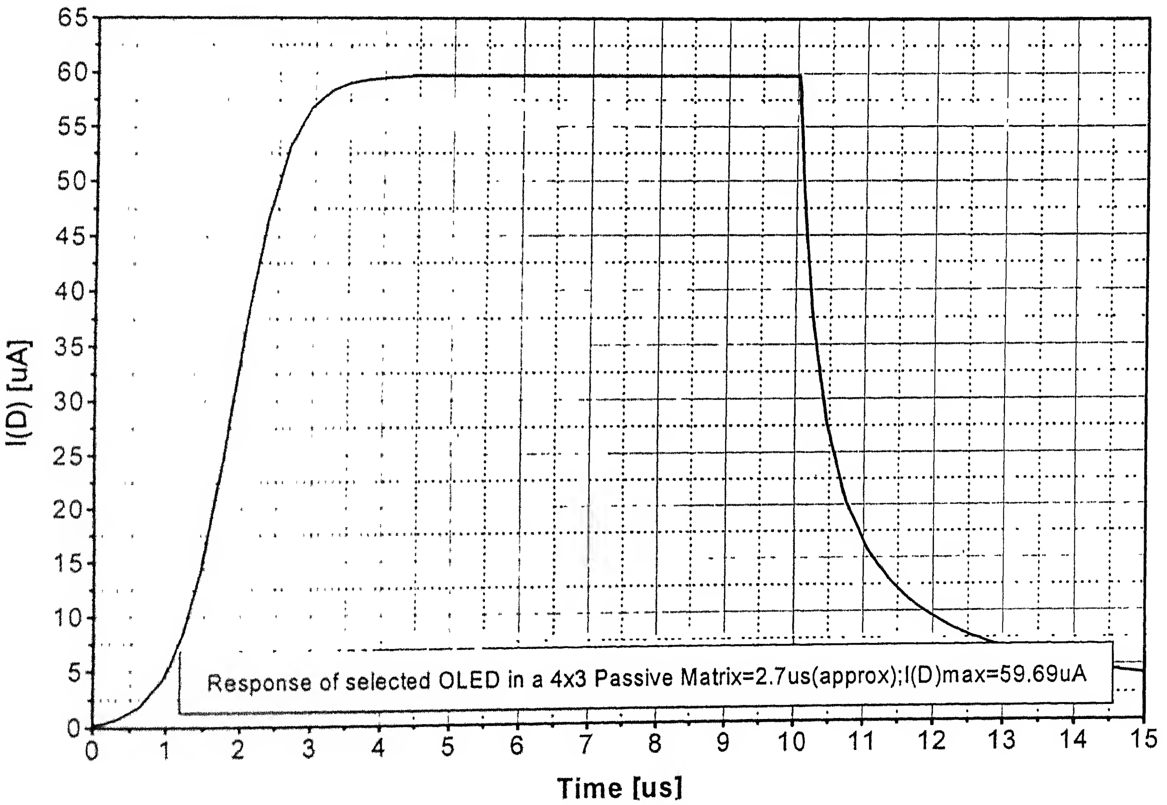


Figure 3.12 Response of the selected OLED in a 4 x 3 Passive Matrix (case 2)

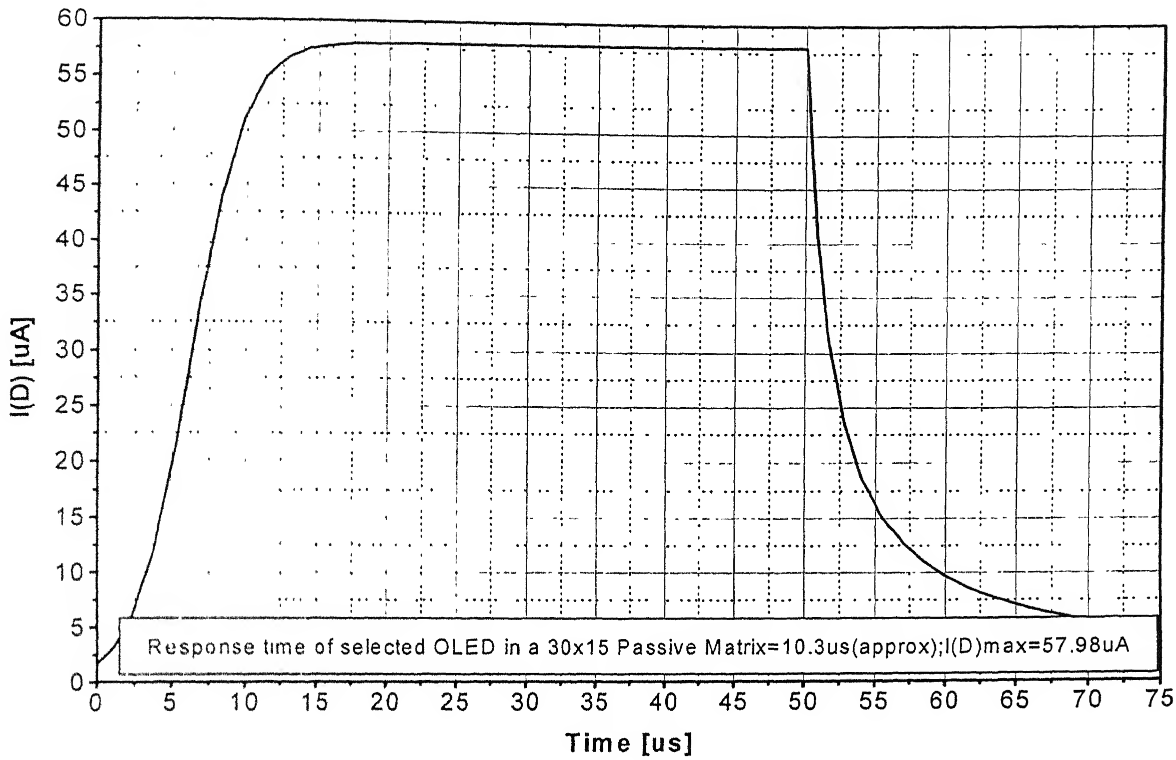


Figure 3.13 Response of the selected OLED in a 30x15 Passive Matrix (case 2)

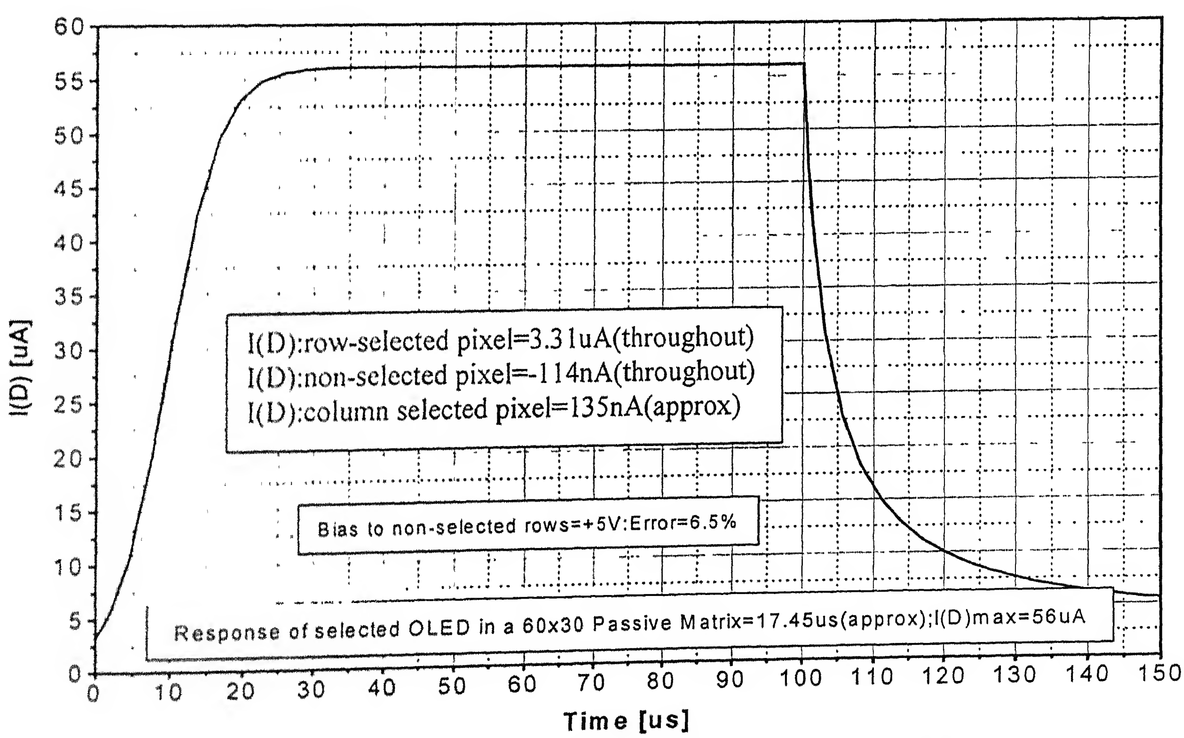


Figure 3.14 Response of the selected OLED in a 60x30 Passive Matrix (case 2)

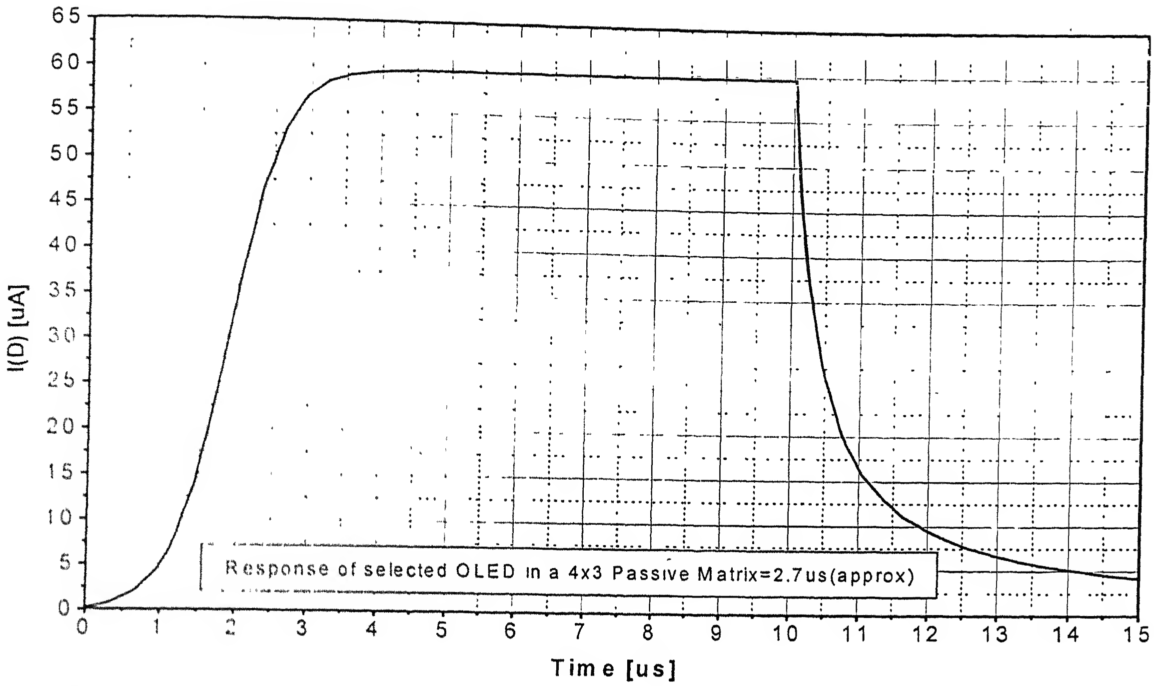


Figure 3.15 Response of the selected OLED in a 4x3 Passive Matrix (case 3)

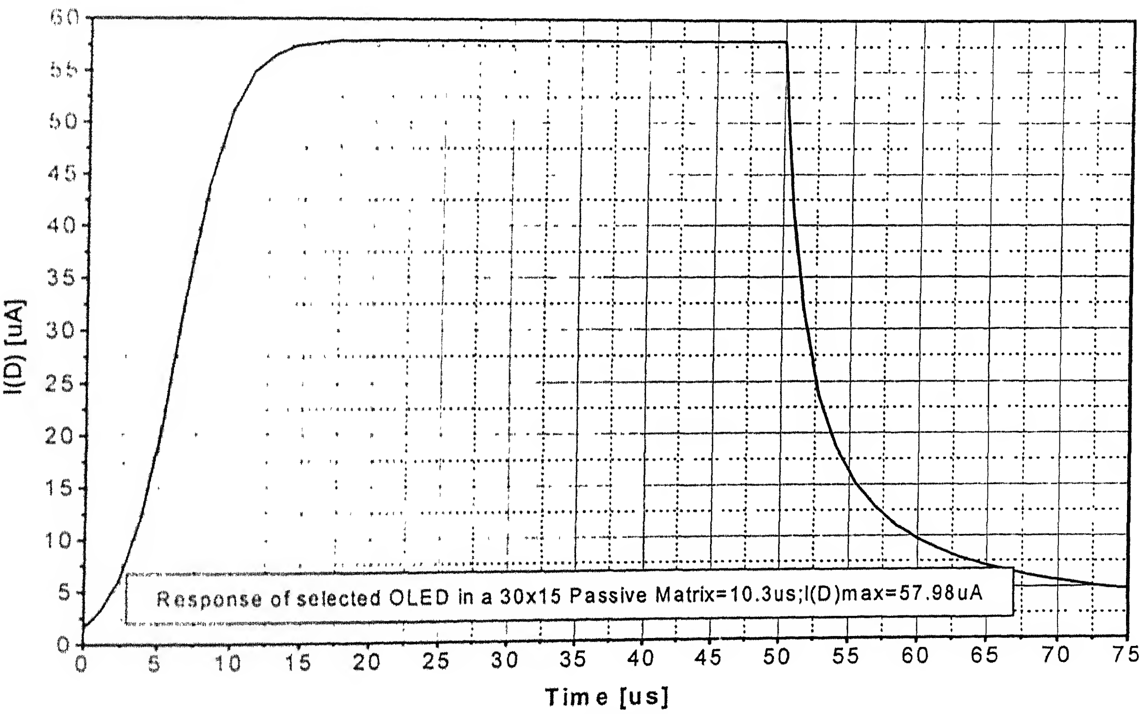


Figure 3.16 Response of the selected OLED in a 30x15 Passive Matrix (case 3)

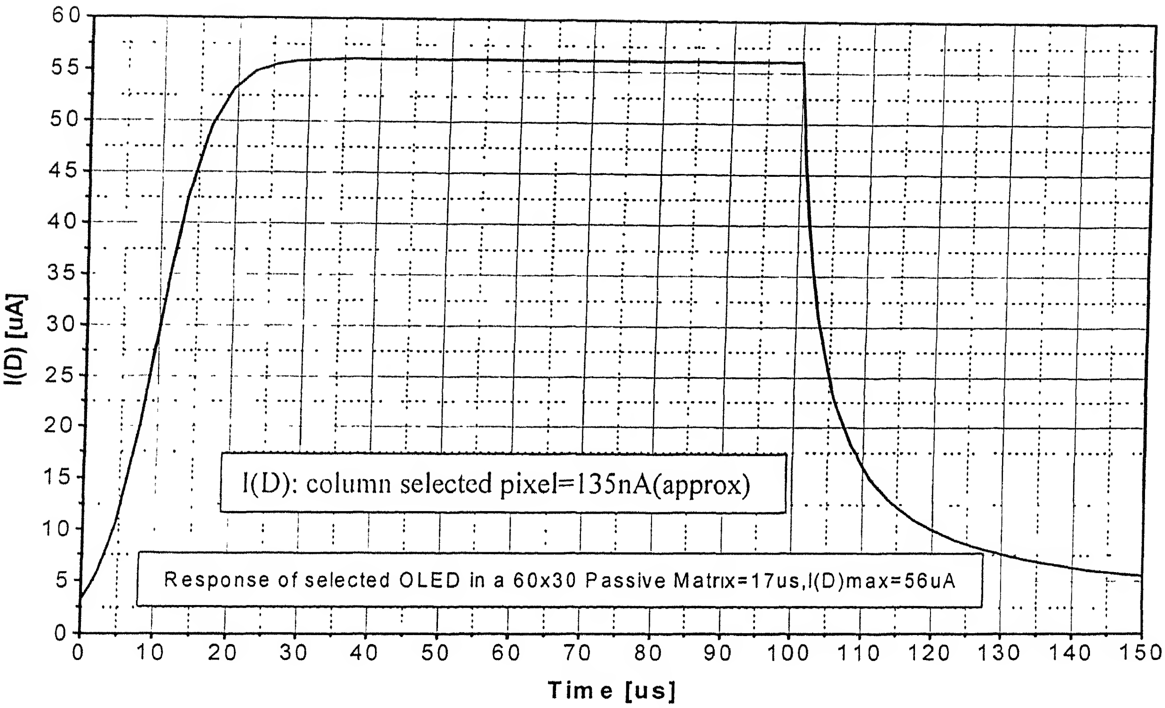


Figure 3.17 Response of the selected OLED in a 60x30 Passive Matrix (case 3)

It is seen that response time of an OLED increases with the size of the passive matrix in which it is used. Results shown in figures 3.18 to 3.20 confirm this statement. Reason for the same is given later in this section, where it shown that the response time of an OLED in a passive matrix depends on the number of rows in the matrix. Comparison of response time of the selected OLED and maximum I(D)'s in a 60x30 passive matrix under different conditions is shown in figure 3.21. From this it is evident that when non-selected rows are open-circuited not only does the response time of the selected OLED is more as compared to cases 2 and 3 but due to significantly large leakage of drive current, I(D)-selected pixel is much less. Reasons for this phenomenon will become obvious later in this section.

Comparison of the response time of a single OLED in passive matrix of different sizes, under different conditions is shown in figures 3.18 to 3.20.

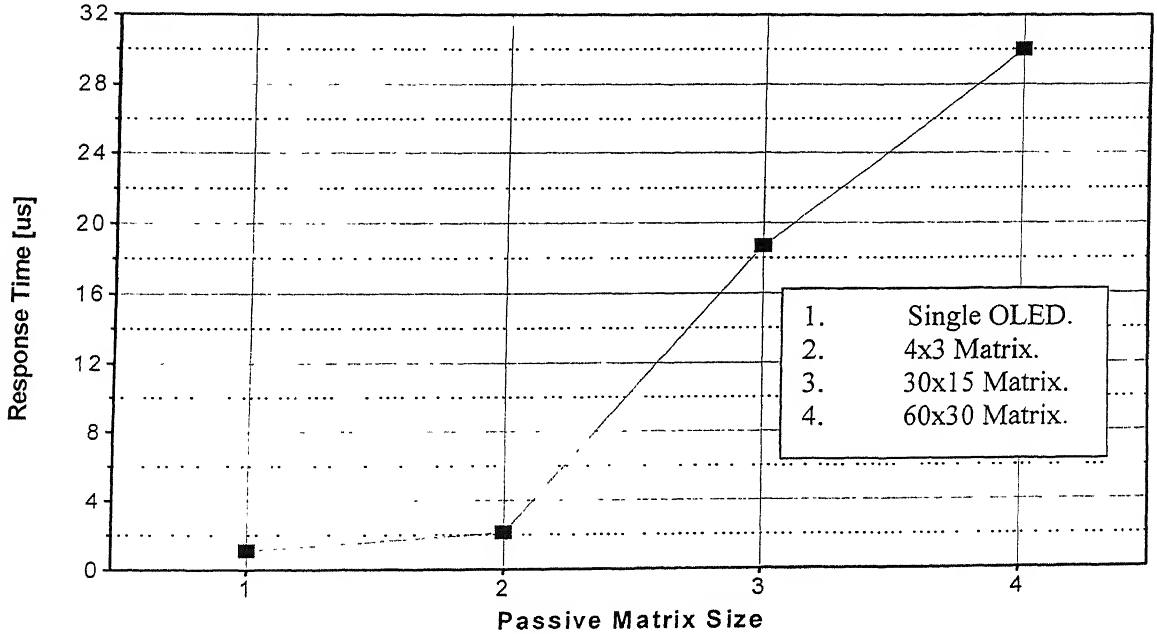


Figure 3.18 Response of selected OLED in Passive Matrix displays of different sizes (case 1)

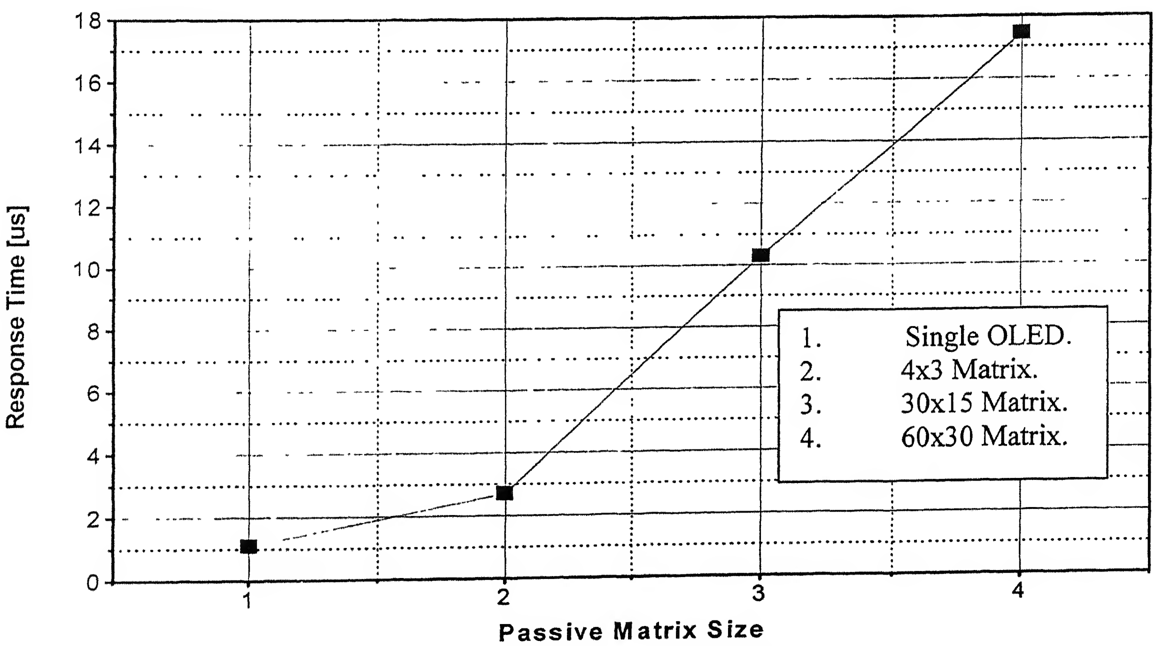


Figure 3.19 Response of selected OLED in Passive Matrix displays of different sizes (case 2)

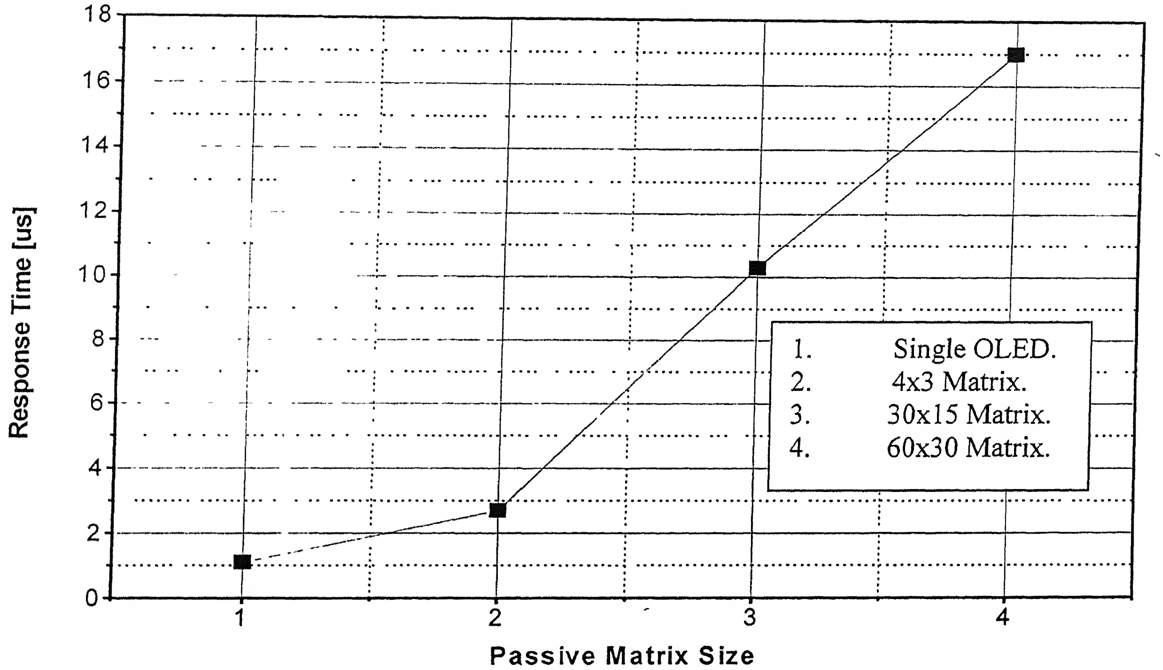


Figure 3.20 Response of selected OLED in Passive Matrix displays of different sizes (case 3)

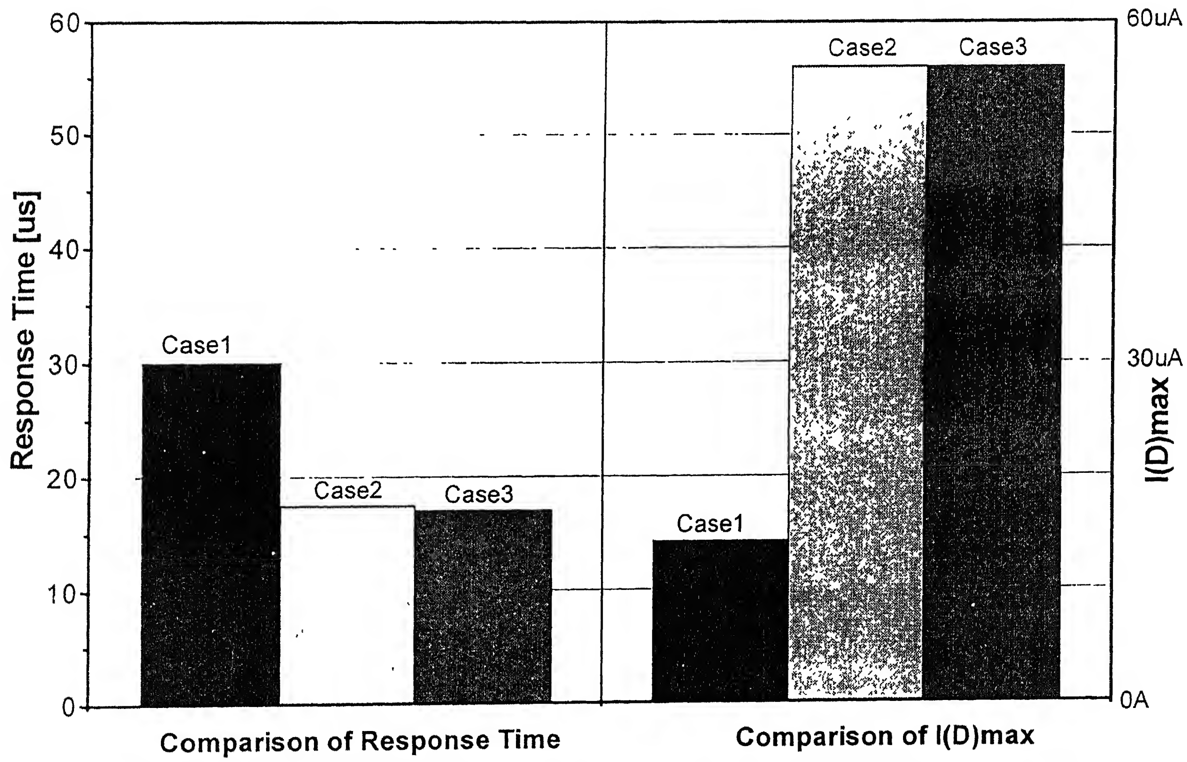


Figure 3.21 Comparison of response time and I(D)s under different conditions in a 60x30 Passive Matrix.

It is of particular interest to note that response of an OLED in a passive matrix depends primarily on the number of rows in the matrix. This is because the response of an OLED in a 4x3, 8x3 and 12x3 (12 columns and 3 rows) passive matrix for case1 has been found to be same i.e. 2.15μs, approximately. The dependence of the response time of an OLED on the number of rows in a matrix is explained here with help of figures 3.22 and 3.23.

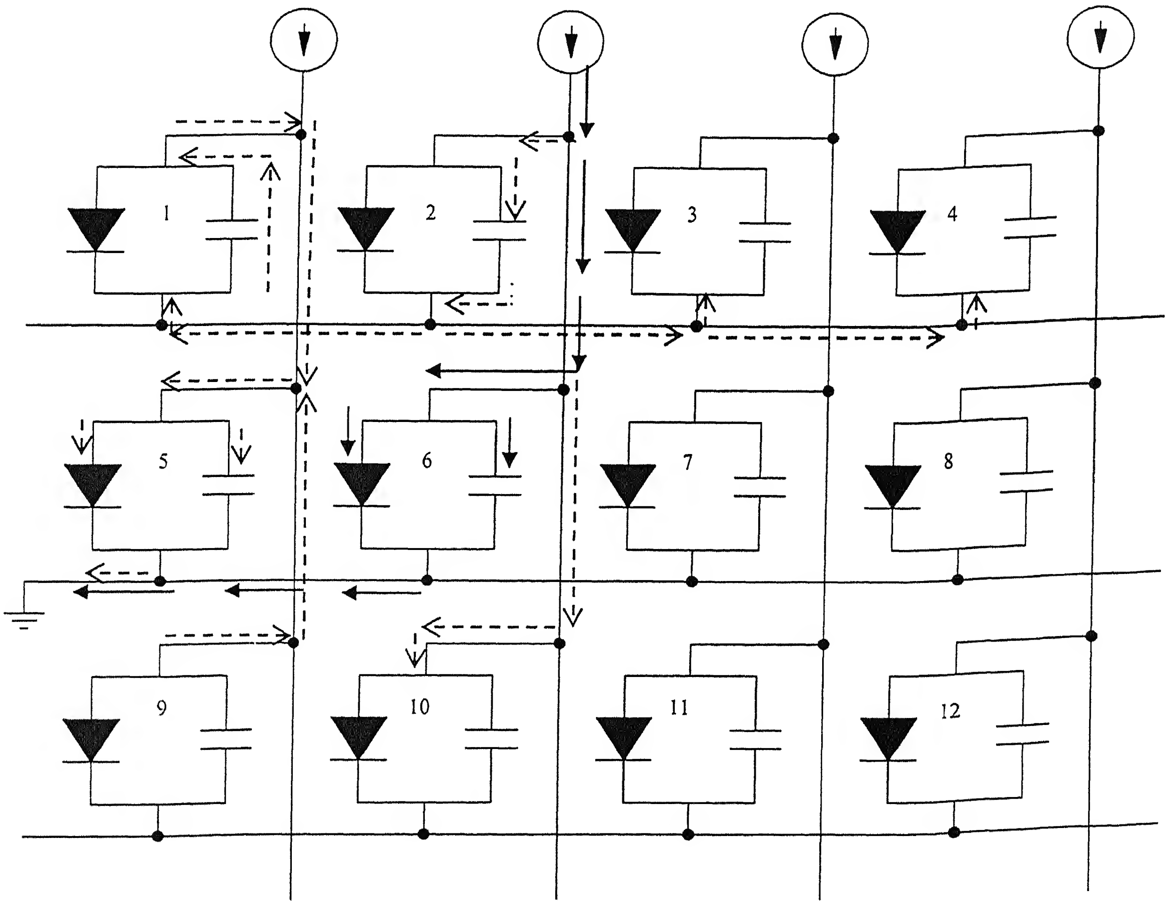


Figure 3.22 Current flow through a passive matrix for case1 (For simplicity resistances are not shown)

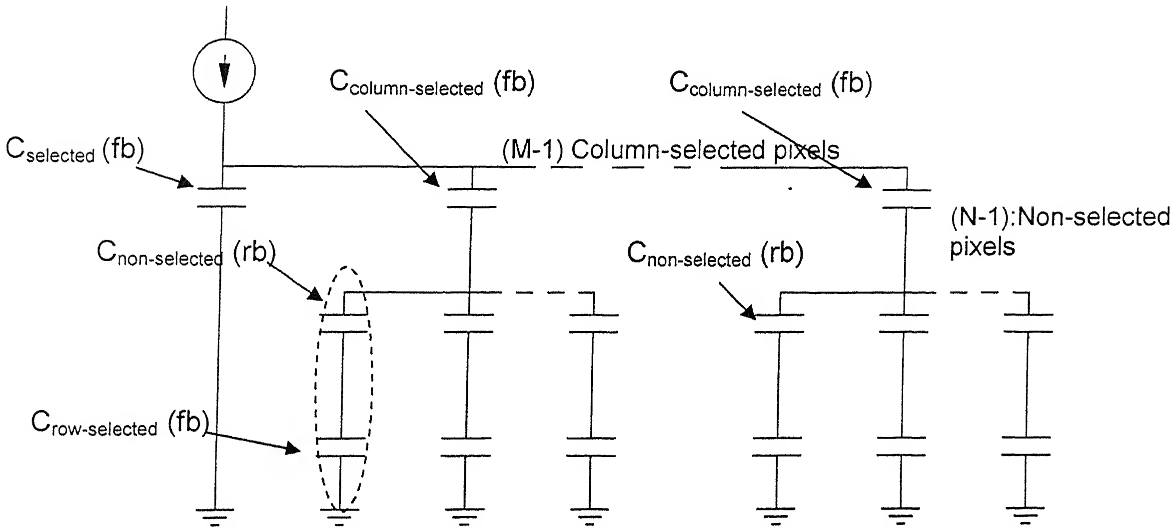


Figure 3.23 (a)

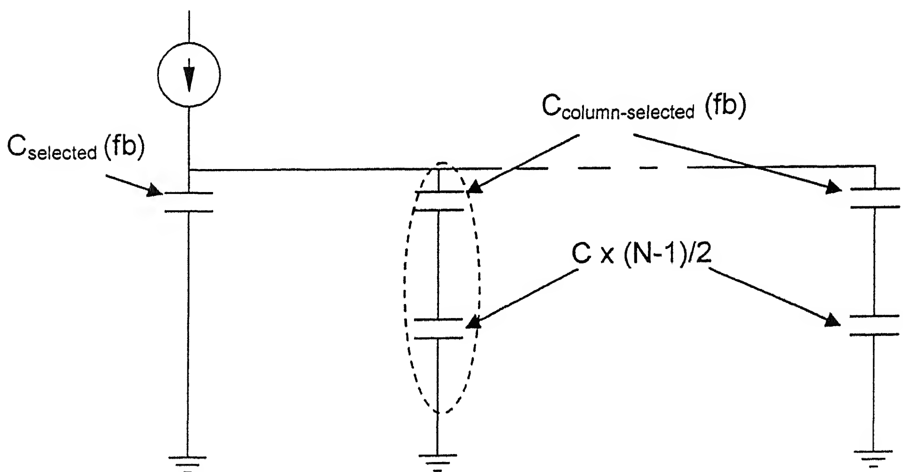


Figure 3.23 (b)

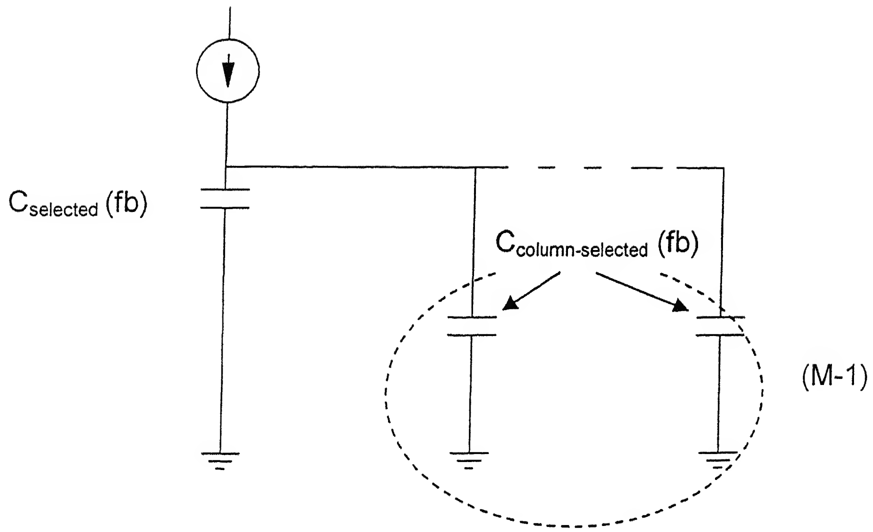


Figure 3.23 (c)

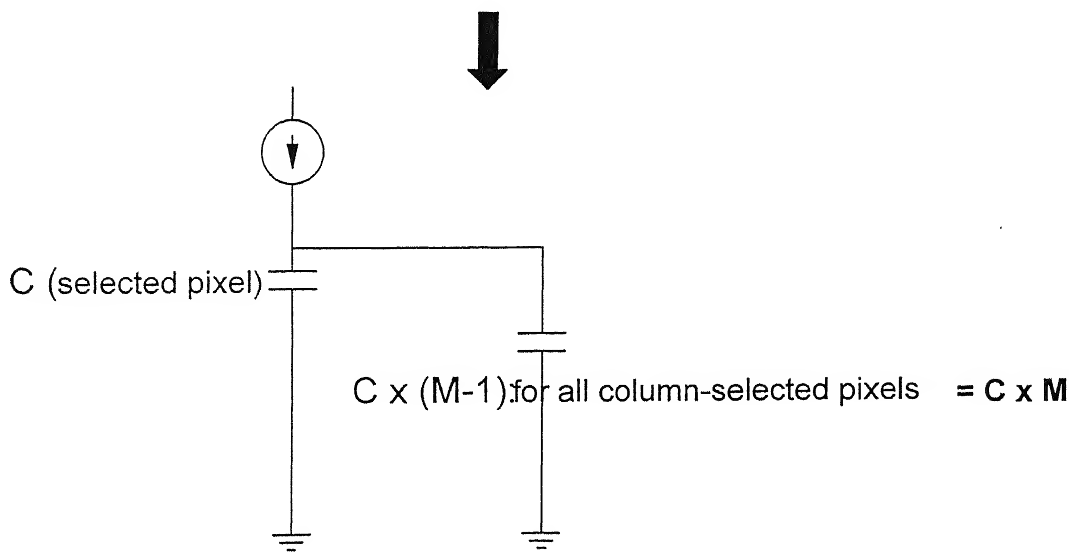


Figure 3.23 (d)

Figure 3.23 Figure showing dependence of response time of OLED on number of rows in a panel

Explanation: The distribution of current in different rows and columns has been studied in different passive matrix each having the same number of rows but different number of columns. The same is explained here using a 4 x 3 passive matrix shown in figure 3.22. Pixel number '6' is selected by giving input to column number 2 and simultaneously row number 2 is grounded. The input current gets almost equally divided into the selected pixel and remaining (M-1) column-selected pixels which get forward biased and are marked as (fb) in figure 3.23. Current from each column-selected pixel gets equally divided into the (N-1) non-selected pixels connected to the same row. The non-selected pixels get reverse biased and are marked as (rb) in figure 3.23 for ease of identification. Current from each non-selected pixel then flows towards the ground through the row-selected pixel connected to the same column. In this way, currents through (M-1) non-selected pixels on a column get accumulated and flow to ground through each row-selected pixel.

Flow of currents through different pixels has been marked on figure 3.22 using different types of arrows. On this basis, figure 3.23 has been used to explain the dependence of response time of an OLED primarily on the number of rows in the matrix. Every $C_{column\text{-}selected}$ is in series with (N-1) $C_{non\text{-}selected}$ on a row, and each $C_{non\text{-}selected}$ is in series with a $C_{row\text{-}selected}$. The effective capacitance of each $C_{non\text{-}selected}$ and $C_{row\text{-}selected}$ combine is therefore C/2. For (N-1) such non-selected pixels on a row it becomes C/2 x (N-1). This is too large as compared to $C_{column\text{-}selected}$ which is in series with this combination. Hence, the effective capacitance at this point becomes approximately C. For (M-1) column-selected pixels it becomes C x (M-1). And as the column-selected pixels are in parallel to the selected pixel hence the overall capacitance is nearly equal to C x M.

Response time $(\Gamma) \alpha$ M x C.

The same can be expressed in the following manner: Let 'I' be the input current to one column. Then current through the selected pixel and each

column-selected pixels will be I/M and response time, $\Gamma \propto M$, where M is the number of rows in the matrix.

It has also been observed that the response time of selected OLEDs in passive matrix decreases as the number of columns being driven increases. This observation has been made on simulating a 60x30 passive matrix. Initially, only one column is given an input of 60μA with remaining (non-selected) columns at 0A. More number of columns are then given this input. Non-selected rows remain open-circuited throughout. It is seen that when only one column is given current input then response of the selected OLED is 30μs, but when same input is given to all the columns i.e. all pixels on one row are selected then the response of all the 60 selected OLED's is 1.1μs, which is the same as the response of a single OLED. Also, when a small input is given to non-selected columns say 0.6μA, which will not cause sufficient average luminance, the response of selected OLED's in passive matrix improves marginally. The same is clearly evident from figure 3.24.

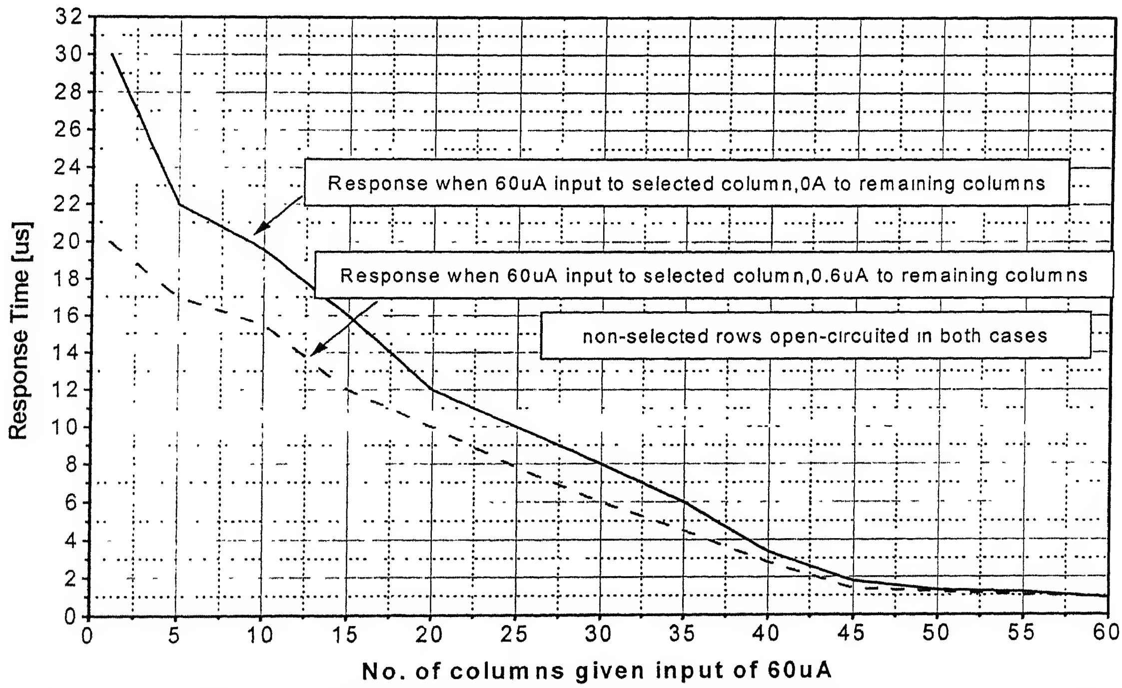


Figure 3.24 Comparison of response time vs No. of columns given input in case of a 60x30 passive matrix.

3.2 Crosstalk in Organic Passive Matrix

Passive matrix organic displays suffer from crosstalk, i.e. emission of light from pixels other than those selected. This problem has received particular attention in the recent past and work to uncover and quantify the causes of crosstalk is currently in progress at a number of technical institutions. But, most of the work [9], [10] so far has been done to understand the reasons for DC crosstalk. However, in this work an effort has been made to identify the reasons for crosstalk arising when passive matrix is operated in dynamic mode. And, methods to overcome this problem have been evolved, simulation results of which have been quite encouraging. A comparison of crosstalk in DC and dynamic mode of operation in case of a 60x30 passive matrix has also been carried out.

3.2.1 Crosstalk in DC Mode of Operation

There are several potential sources of crosstalk. Some have been identified [9] as:-

- Display resolution: the greater number of pixels required for higher resolution displays creates more available parallel conduction paths.
- Rectification ratio: higher the rectification ratio of the OLED smaller is the magnitude of the leakage current flowing for the same bias.
- Reverse leakage currents: parallel leakage paths compromise the diode action under reverse bias.
- Optical crosstalk: due to internal reflection.
- Electrode resistance: resistances of row and column electrodes decrease image uniformity [10].
- Faulty pixels: location of faulty pixels causes crosstalk.

A 4x3 passive matrix shown in figure 3.25 has been used to explain how unwanted light is produced.

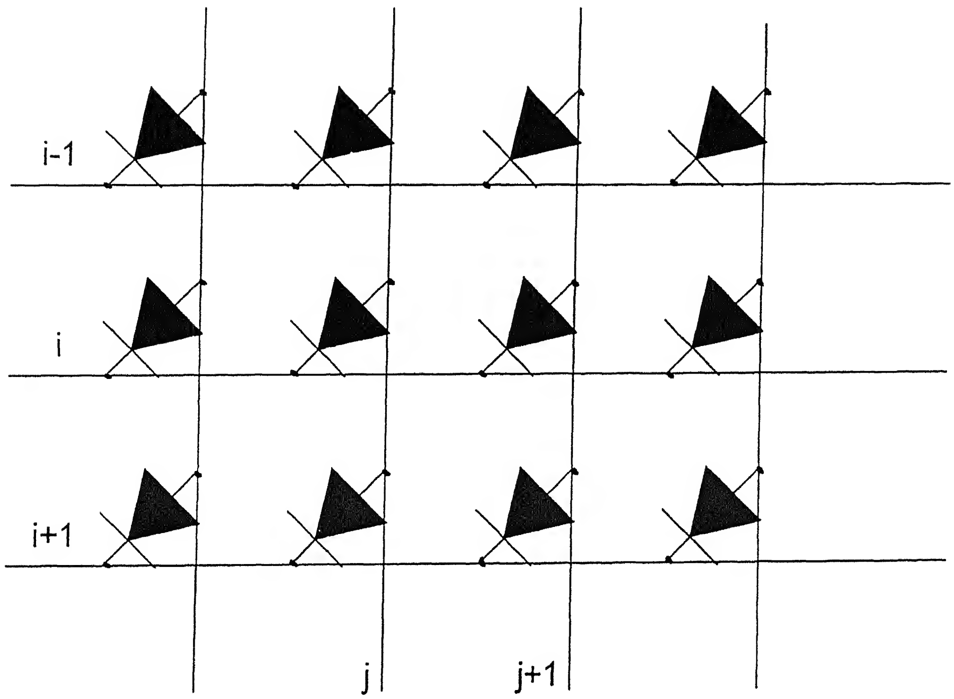


Figure 3.25 Circuit diagram of a 4 x 3 Passive Matrix

A large number of pixels are unintentionally reverse biased when a pixel is addressed. For example, when pixel (i, j) is addressed, in the circuit branch containing pixels (i, j+1), (i+1, j+1), and (i+1, j), pixel (i+1, j+1) gets reverse biased. Leakage currents flow through unintentionally formed circuit branches comprising reverse biased OLEDs. The total leakage current drawn from a column driver through all the similar branches depends on the brightness profile of the addressed row. Two extreme cases are discussed here.

- Case1: All the pixels in the selected row are driven to the same brightness- in this case the voltages across all the pixels in the addressed row are equal. The total leakage current through other pixels is, therefore, also zero.
- Case2: One pixel (i, j) in the addressed row is driven to full brightness, with all others turned off- in this case the array can be represented by an equivalent circuit shown in figure 3.26.

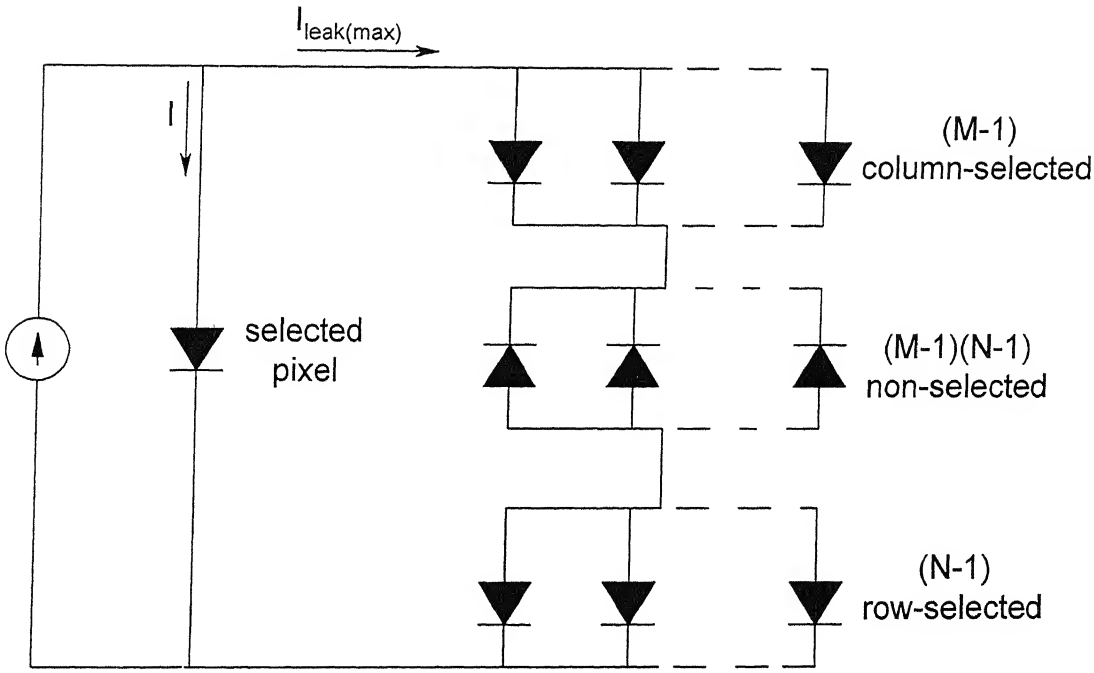


Figure 3.26 Equivalent circuit of a PM OLED array when only one pixel is selected

When driven by a current I, the voltage V across pixel (i, j) is also applied to the branch composed of row-selected, non-selected and column-selected pixels forcing a leakage current, $I_{leak(max)}$, through this branch. In the intermediate cases (where the pixels in the addressed row are driven to different brightnesses), the leakage current extracted from each column driver is less than $I_{leak(max)}$, since less voltage is dropped along the leakage currents paths as compared to case 2. Hence, the leakage current extracted from each column driver ranges from zero to $I_{leak(max)}$. Assuming the current source provides a fixed current for a given pixel brightness, the current I actually flowing through an addressed pixel depends on the leakage current.

Simulation on a 60x30 passive matrix

DC analysis has been performed on a 60x30 passive matrix for different conditions (cases) listed here:-

- Case1: DC input of 60μA given to one column, remaining columns open-circuited/at 0A. Non-selected rows open-circuited.
- Case2: DC input of 60μA given to one column, remaining columns open-circuited/at 0A. Non-selected rows at +5V dc (refer section 2.4).
- Case3: DC input of 60μA given to one column, remaining columns grounded. Non-selected rows at +5V dc (refer section 2.4).

Results obtained are given in the table 3.1 below:-

I(D)'s	Case 1	Case 2	Case 3
Selected pixel (μA)	14.582	56.086	56.086
Column-selected pixel (μA)	1.566	0.135	0.135
Row-selected pixel (μA)	0.77	3.306	1.7×10^{-30}A
Non-selected pixel (nA)	-26.545	-113.997	-129.4

Table 3.1 Results for DC mode analysis of a 60x30 PM OLED

Deductions:-

Case1:

I(D) of each column-selected pixel gets equally distributed into (N-1) non-selected pixels connected to the same row, 59 in a 60x30 matrix. Therefore

$$I_{non\text{-}selected} = I_{column\text{-}selected}/59$$
$$=26.5\text{nA (approx)}$$

$$I_{row\text{-}selected} = I_{non\text{-}selected} \times (M-1)$$
$$=0.77\mu\text{A (approx)}.$$

Case2:

In this case leakage current is small as an external reverse bias is applied to non-selected and column-selected pixels. Amount of current flowing through the column-selected pixels depends upon the magnitude of the reverse bias. Due to reverse bias on non-selected rows a constant reverse leakage current flows through the non-selected pixels. In this case it is found to be 113.997nA. This current of all non-selected pixels connected to a column combines and flows to ground through the row-selected pixel on that column. Hence, 113.997nA x 29 (i.e. M-1)=3.306μA.

Case3:

The results for this case are same as that for case 2 except that due to non-selected columns being grounded the reverse current that flows through non-selected pixels does not flow to row-selected pixels. Hence, negligible or no current flows through the row-selected pixels in this case. Small leakage current flows through the column-selected pixels if the non-selected rows are at lower voltage as compared to the voltage developed on the selected column on which these are connected.

3.2.2 Crosstalk in Dynamic Mode of Operation

Crosstalk due to flow of currents on undesired paths in a passive matrix is similar to that already seen in section 3.2.1 for DC mode of operation. However, in the dynamic mode of operation due to constant pulsing of drive current there is leakage of currents not only through the diodes but also across the capacitances of the OLEDs.

Simulations on a 60x30 passive matrix

Analysis of the dynamic mode of operation has been performed on a 60x30 passive matrix for different conditions (cases) listed here:-

- Case1: Pulse of 60μA (ON for 30μs, pulse period of 34.72μs) given to one column, remaining columns open-circuited/at 0A. Non-selected rows open-circuited.
- Case2: Pulse of 60μA (ON for 30μs, pulse period of 34.72μs) given to one column, remaining columns open-circuited/at 0A. Non-selected rows at +5V dc (refer section 2.4).
- Case3: Pulse of 60μA (ON for 30μs, pulse period of 34.72μs) given to one column, remaining columns grounded. Non-selected rows at +5V dc (refer section 2.4).

Results obtained are given in the table 3.2 below:-

Pixel parameters	**Case 1**	**Case 2**	**Case 3**
I(D):Selected pixel (μA)	14.23	56.05	56.06
I(D):Column-selected pixel (μA)	1.6	0.135	0.135
I(D):Row-selected pixel (μA)	0.78	3.306	$1.7\text{x}10^{-30}$A
I(D):Non-selected pixel (nA)	-26.6	-113.997	-129.4
Potential at selected column (V)	4.4	5.66	5.66
Potential at non-selected column (V)	1.8	3.05	0
Potential at non-selected row (V)	1.9	5	5

Table 3.2 Results for dynamic mode analysis of a 60x30 PM OLED

Deductions:-

From results given at tables 3.1 and 3.2 it is clear that the currents through the diodes in both the DC mode and the dynamic mode of operations are more or less similar. It proves that leakage pattern of currents is generally same in both the cases, except that in dynamic case leakage path also exists through OLED's capacitances. As the ON period of the drive current pulse is increased it is observed that averaged-integrated value of I(D)'s taken for a complete frame time approach the results obtained in case of DC analysis. The averaged-integrated values of I(D)'s have been obtained as given below:

$$\int (I(D)).dt * \frac{T_r}{T_f} \qquad \text{.............................(5)}$$

Here, T_r is the ON time of drive current pulse and T_f is the frame time.

As seen, the actual I(D)'s (output), are mostly different from the desired I(D)'s (output) due to crosstalk. Ideally, the actual output should be as close to the value of input current as possible so that the crosstalk is minimum. Here, error in actual and desired (ideal) I(D)'s is defined as a percentage. Figure 3.27 gives a comparison of errors in actual I(D)'s vis-a-vis the desired (ideal) I(D)'s. From the figure it is clear that as the ON time of the drive current pulse is increased the final value of I(D)'s move close to the values of I(D)'s obtained in the case of DC mode of operation.

$$\%Error = \frac{(Ideal - Actual)}{Ideal} * 100 \qquad \text{.............................(6)}$$

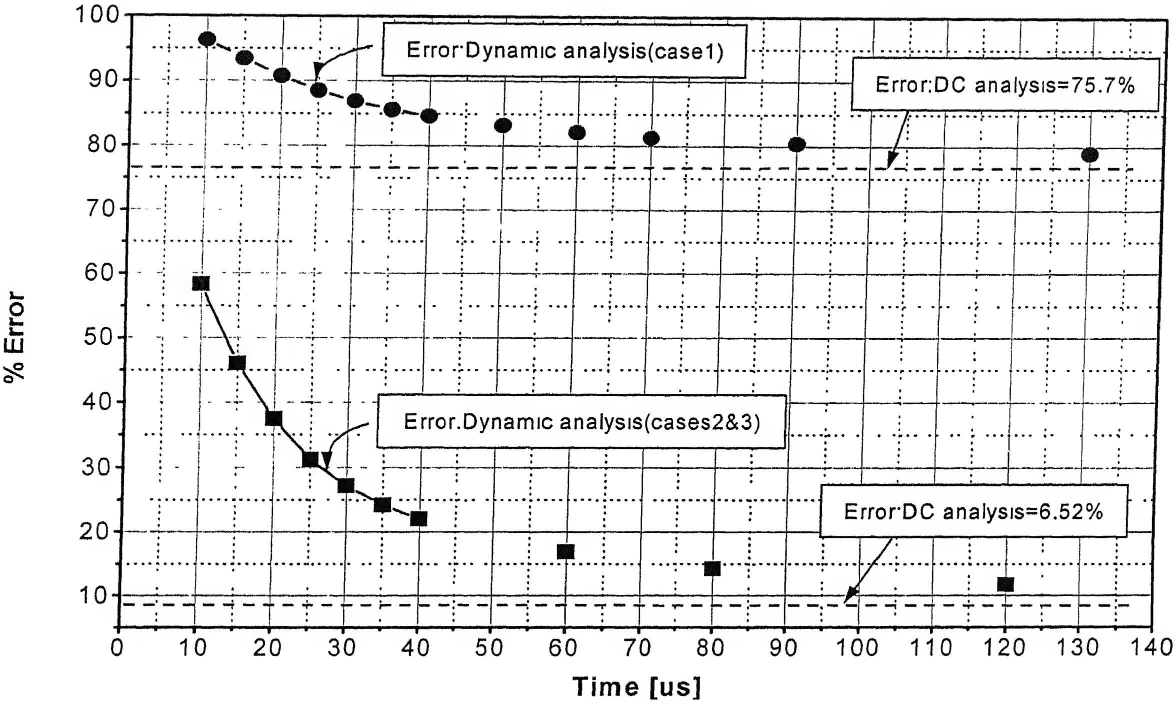


Figure 3.27 Comparison of errors in actual I(D)s for DC and Dynamic analysis.

Simulation plots of I(D)'s through the selected pixels for cases 1, 2 and 3 have already been shown in figures 3.11,3.14 and 3.17, respectively. Simulation plot of I(D)'s through different pixels for case1 is shown as figure 3.28.

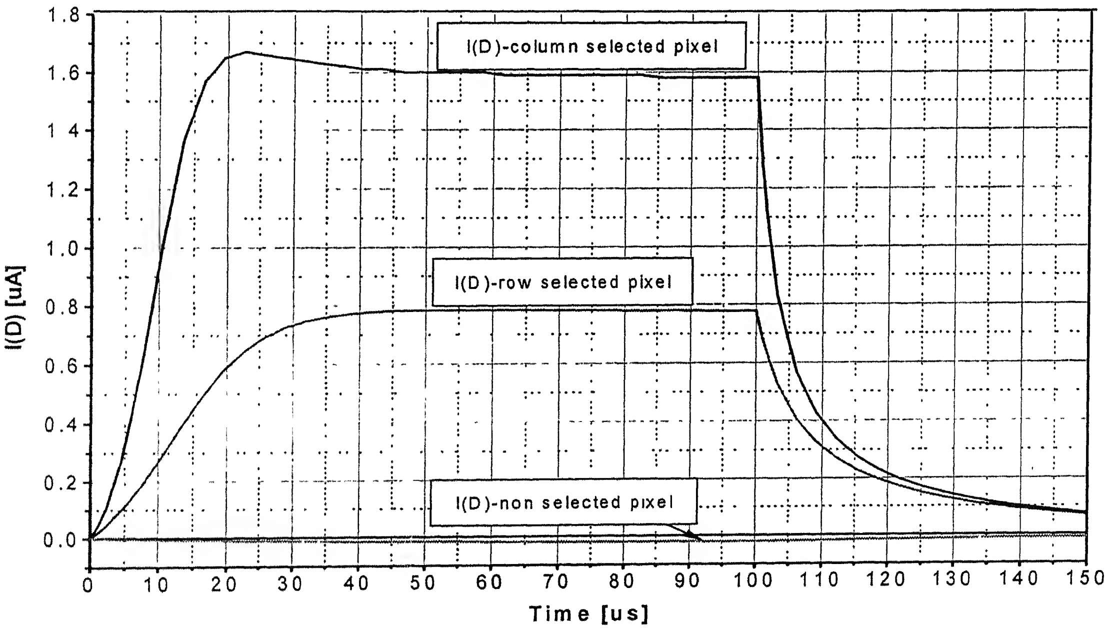


Figure 3.28 I(D)'s of different pixels in a 60x30 Passive Matrix for case1.

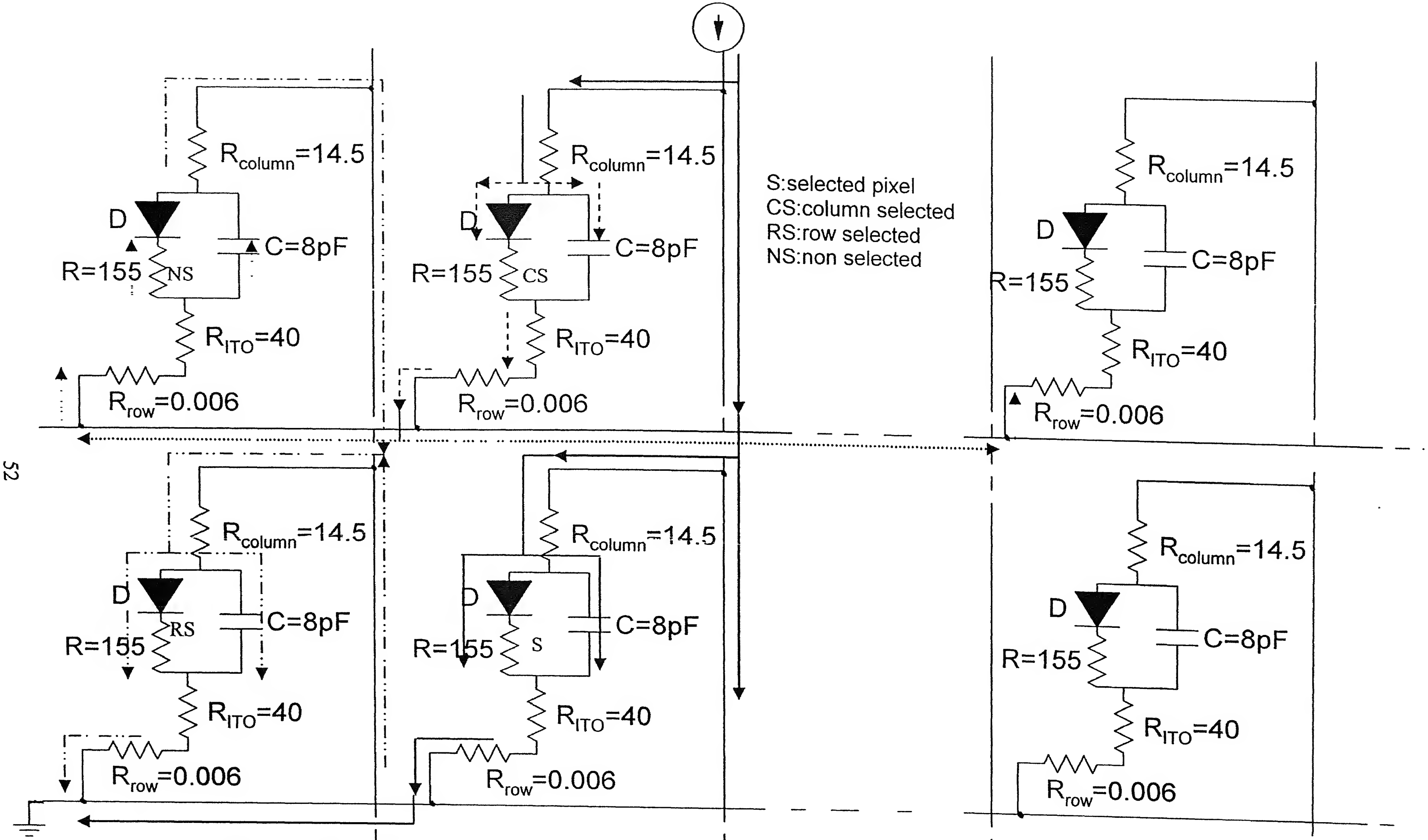


Figure 3.29 Flow of currents through different pixels in a passive matrix

The flow of currents through different pixels for case 1, is shown in figure 3.29. The reasons for small leakage of currents in cases 2 and 3 are same as that for DC mode of operation. It has been observed that magnitude of I(D)'s through row-selected pixels increases quite significantly due to leakage as the number of columns selected during scanning of one row are increased. This is clearly evident from figure 3.30.

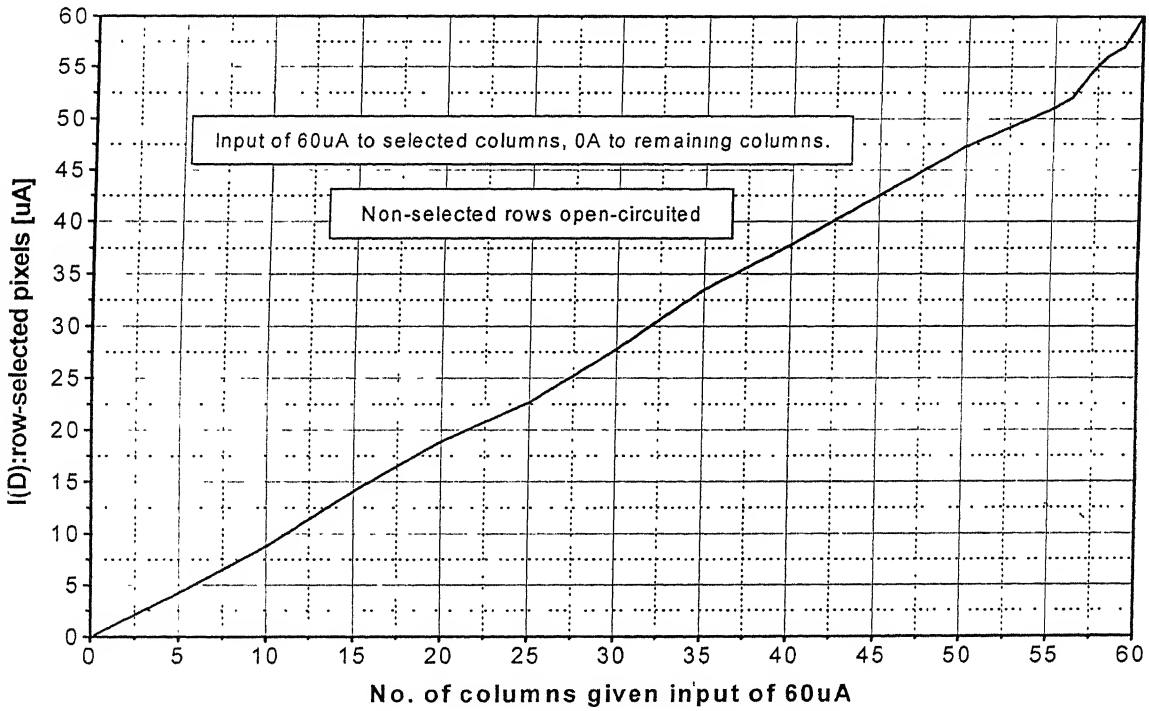


Figure 3.30 Comparison of I(D)s in row-selected pixels vs No. of columns driven by 60μA in a 60x30 Passive Matrix

<u>Limitation of Cases 2 and 3:</u> However, though actual I(D)'s in case 2 and 3 are more close to the desired outputs as compared to case 1 because of smaller leakage of input drive current through non-selected pixels-it is seen that different DC bias are required for different drive currents. This is because different potentials develop at the selected column and the non-selected columns for different drive currents. From figures 3.31 and 3.32 it is seen that when drive current pulse is 6μA then a DC voltage of +5V on non-selected rows is too large as the actual I(D) is

approximately 8.5μA instead of the desired 6μA. When, instead of +5V a bias of +3V is applied, the actual I(D) of the selected pixel in a 60x30 passive matrix is approximately 4.4μA. This happens because, when the potential at the non-selected row (due to reverse bias applied) is more than the potential developed at the selected column due to the drive current then current flows through the column selected pixels in the reverse direction and this reverse current from all column-selected pixels flows to ground through the selected pixel. Due to this problem, complexity in designing large size matrix with this technique will be enormous, as it is practically not possible to apply different bias to non-selected rows depending upon the input currents. But, Zhang Bu-xin, et al. [7] have claimed to have developed a 96x60 passive matrix with green OLEDs using this technique and have not observed crosstalk between pixels.

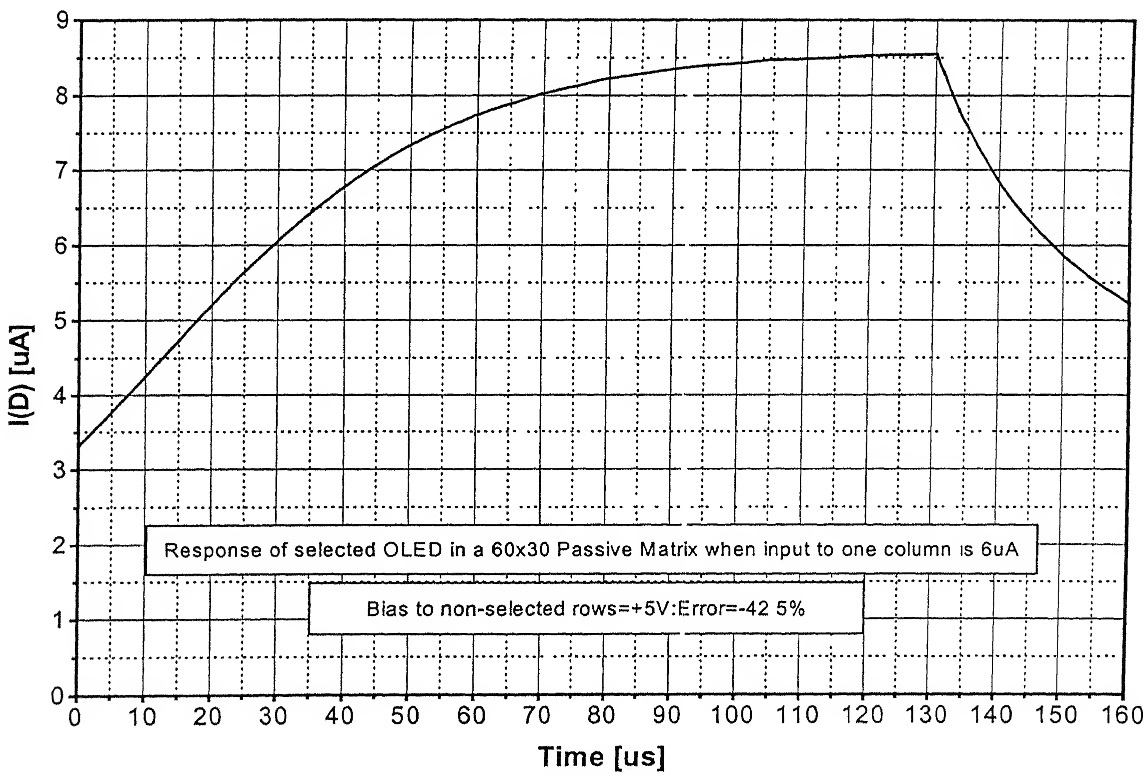


Figure 3.31 I(D) through selected pixel in a 60x30 PM OLED for cases 2 and 3 when drive current is 6μA and bias to non-selected rows is +5V.

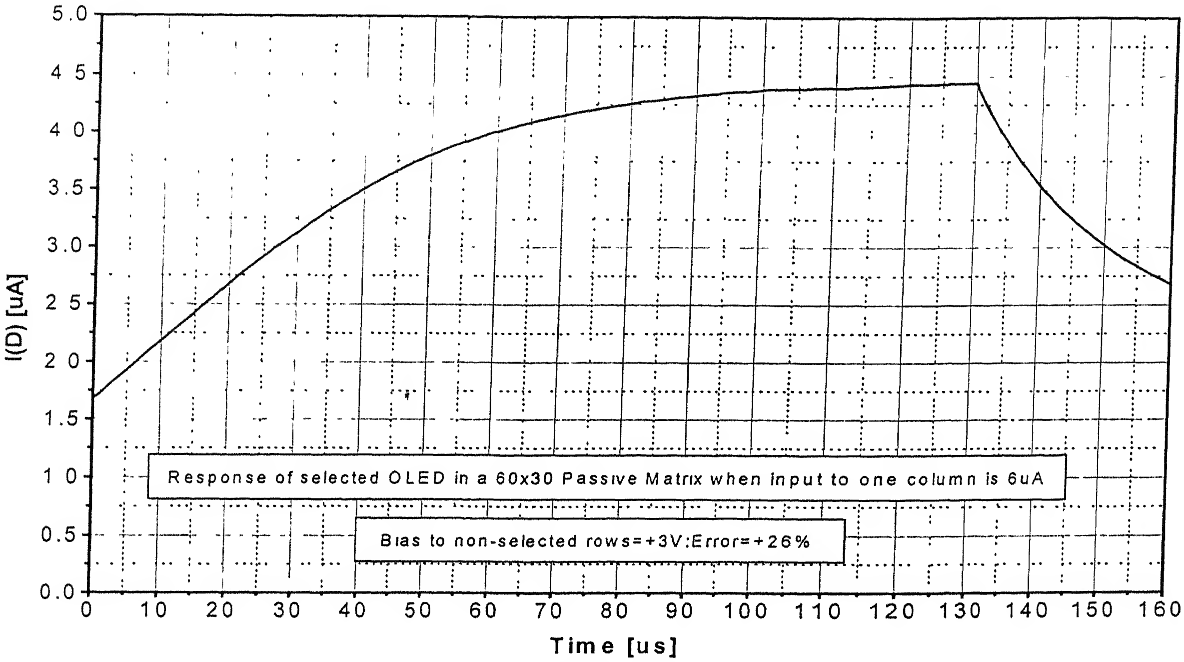


Figure 3.32 I(D) through selected pixel in a 60x30 PM OLED for cases 2 and 3 when drive current is 6µA and bias to non-selected rows is +3V.

Percentage errors for different cases: In order to have a better idea of crosstalk between pixels; drive currents of different magnitudes are given to 30 different columns with one row being grounded. Details of these currents are given in table 3.3. The remaining 30 columns are either open-circuited/at 0A and the non-selected rows are open-circuited(case1), remaining columns are either open-circuited/at 0A/grounded and the non-selected rows are at +5V(case2) and in case3 the remaining 30 columns are grounded but the non-selected rows are open-circuited.

Drive current (µA)	No. of columns driven
6	5
10	3
20	4
30	5
40	5
50	3
60	5

Table 3.3 Drive currents for different columns

Percentage error in case of each input/output has been measured by taking the averaged-integrated values of I(D)'s as explained earlier in the work, (equations 5&6). The percentage errors for these cases are shown in figure 3.33. It is observed that the error is maximum in case3 as I(D)'s through column-selected pixels find a direct path to ground through the (N-1) non-selected pixels connected to the same row, as a result the leakage through the column-selected pixels increases and $I(D)_{selected}$ decreases.

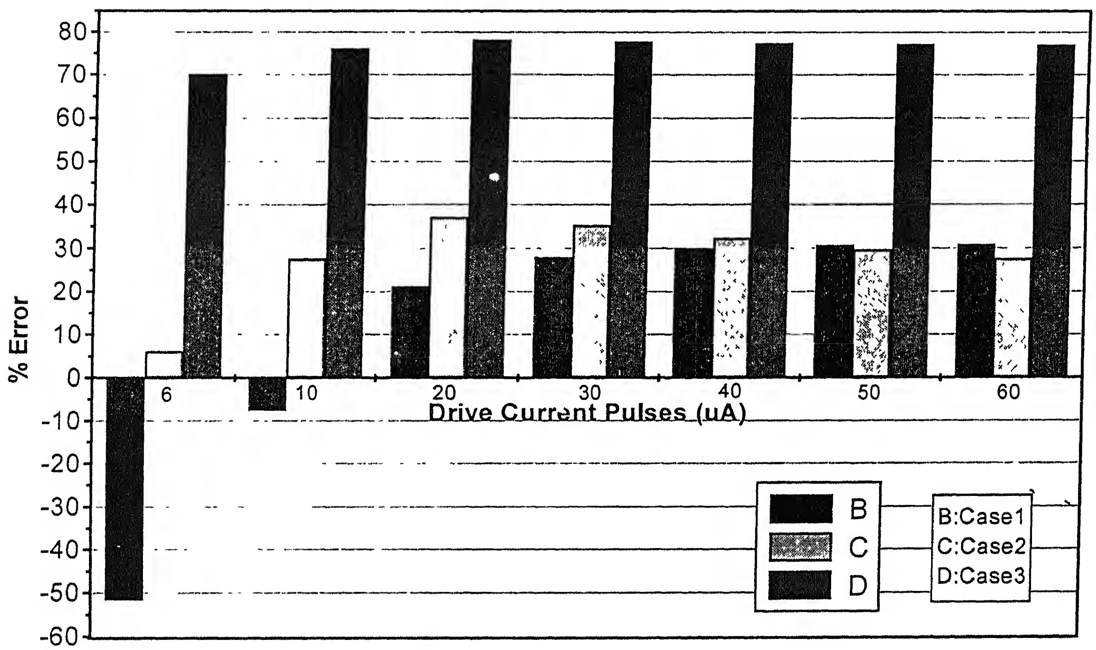


Figure 3.33 Percentage errors for different drive currents for different cases.

Crosstalk for different cases when rows are scanned one after another has been studied in a 4x3 passive matrix. The plots of I(D)'s of selected pixels for the following cases are displayed as figures 3.34 and 3.35.

- Case1: Inputs of 10μA, 60μA and again 10μA are given to one column (number 2), one after another for a time period of 34.72μs each (ON time-30μs), remaining columns are either open-circuited or, are at 0A. The selected row is grounded in the following sequence for duration of 34.72μs each. At first row1,

followed by row 2 and in the end row 3. The non-selected rows are open-circuited.

- Case2: Inputs of 10μA, 60μA and again 10μA are given to one column(number 2), one after another for a time period of 34.72μs each(ON time-30μs), remaining columns are either open-circuited/at 0A/grounded. The selected row is grounded in the following sequence for duration of 34.72μs each. First row1, followed by row 2 and in the end row 3. The non-selected rows at +4V.

As expected, it is seen that in case 1 current flows through undesired paths i.e. through pixel number 2, 6 and 10 (column-selected) even when these are not selected. However, leakage and hence crosstalk is less in case 2. Here, I(D2), I(D6) and I(D10) are the diode currents through the pixels on the selected column.

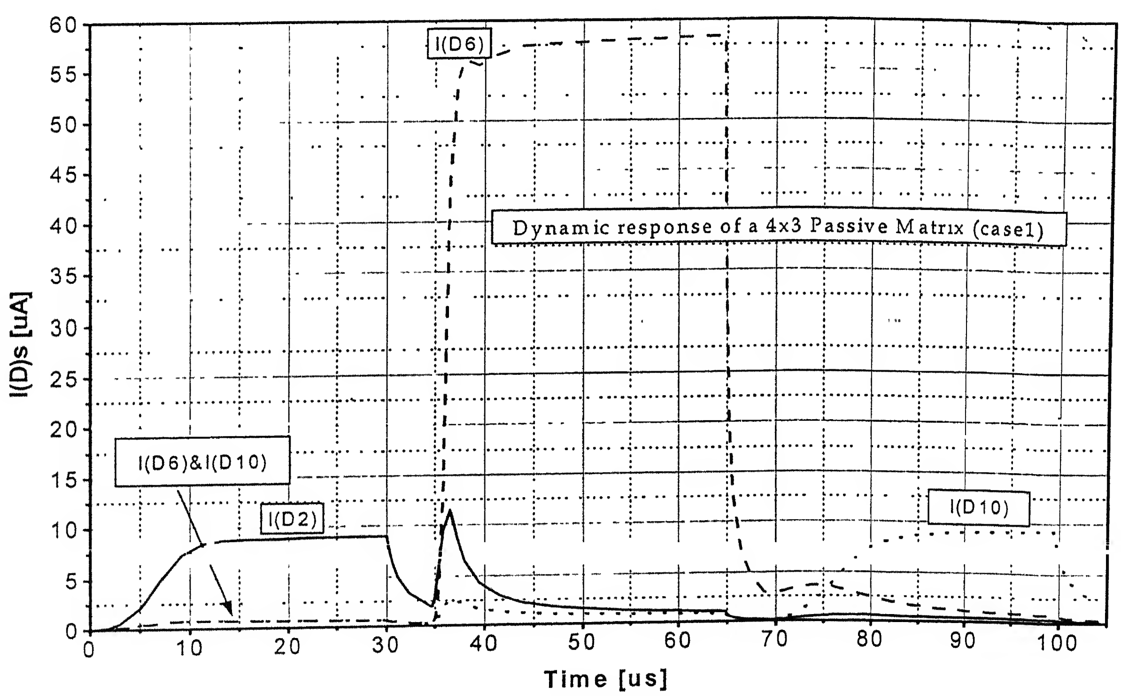


Figure 3.34 Dynamic response of a 4x3 Passive Matrix (Case 1).

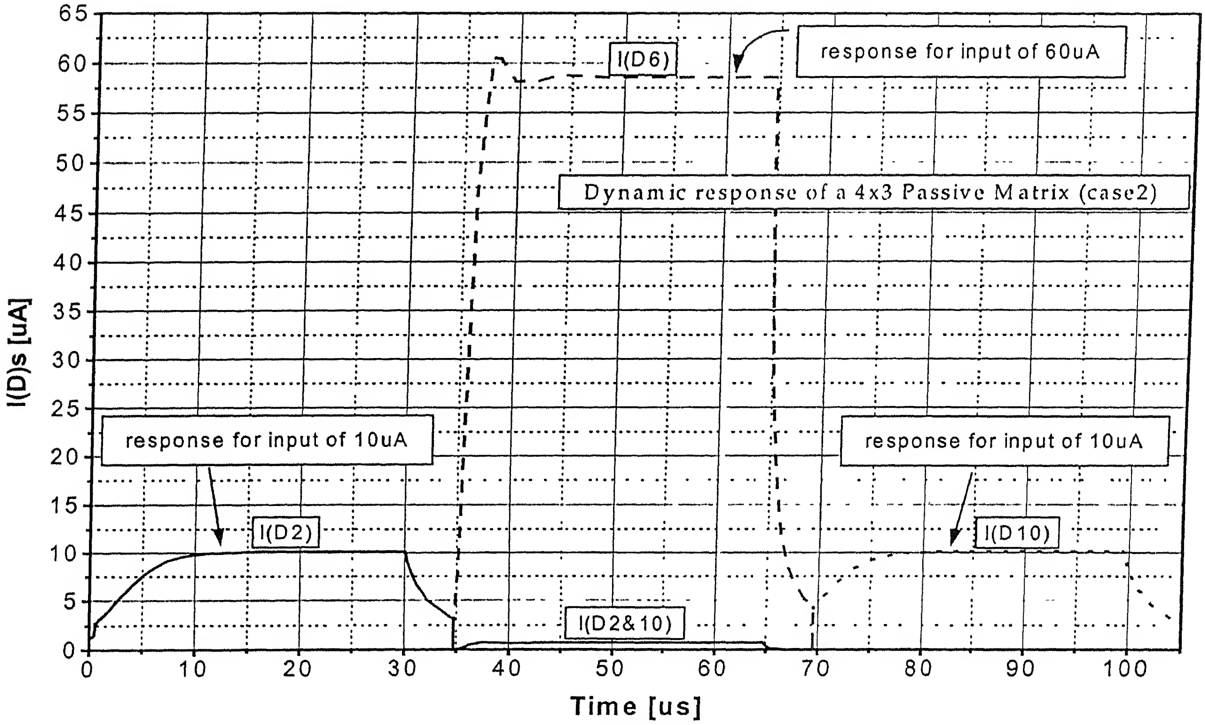


Figure 3.35 Dynamic response of a 4x3 Passive Matrix (Case 2).

3.3 Modified "Passive" Matrix Array

In sections 3.1 and 3.2 it has been seen that no matter what technique is employed for driving columns or scanning of rows, problems of poor response time and crosstalk are not completely removed. The magnitude of error varies from the 'worst case' (when input is given only to one column) to 'best case' (when all columns are driven). In order to overcome these problems a small modification in the design of passive matrix has been tried out in this work. Circuit simulations of the same have shown almost negligible crosstalk and extremely low response time even in the worst case situation.

In this design of passive matrix an active element (p-type poly-Si TFT) has been incorporated in the circuit of each pixel so that current flows through the OLED only when the transistor (TFT) is 'ON' i.e. when it's gate-to-source voltage (V_{GS}) is more than it's threshold voltage (V_T): $| V_{GS} |>| V_T |$.

The modified organic pixel model is shown in figure 3.36.

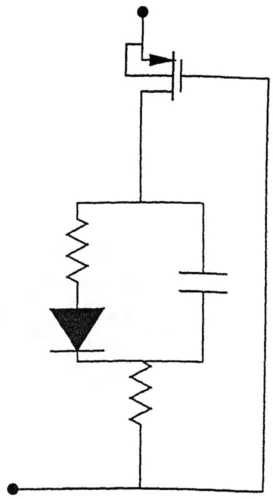


Figure 3.36 Modified model of organic pixel

3.3.1 Design of Modified Passive Matrix

Passive matrix of different sizes has been designed using the modified pixel model at the intersection of rows and columns. TFT used in the design is of poly silicon (poly-Si). Therefore, it can be formed at the substrate itself. Presently available a-Si and poly-Si FET's and TFT's performance satisfy current requirements of organic displays. However, high performance FET's and TFT's with much improved field effect mobilities are being developed [1]. The parameters of a typical p-type poly-Si TFT used in this work are given at Appendix 'A'. The OLED is to be formed between the gate and drain of the TFT in conventional manner. A 4x2 modified OLED passive matrix is shown in figure 3.37. With this modification the matrix obtained is no more a "passive matrix" in true sense. However, this modified model is still very simple as compared to active matrix.

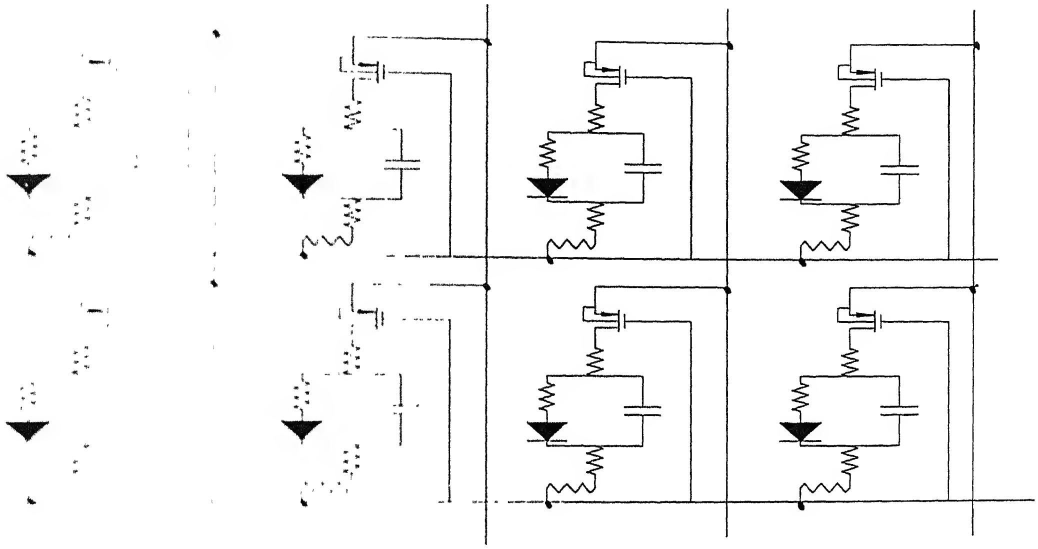


Figure 3.37 Modified Organic Passive Matrix

3.3.2 Operation of Modified Passive Matrix

To understand of the modified passive matrix, consider that only one column of the modified matrix is driven by a current pulse and the non-selected columns are either at 0A or grounded. The selected row is grounded. Consequently only one pixel is selected. An observation of interest is that when a poly-Si p-type TFT is used the voltage of the current source required to generate the drive current pulse is quite high. For a 60x30 matrix the simulation results show that the current source should be at a potential of approximately 20V for I(D)'s to attain desired optimum values.

As a result, the selected columns are at a high potential of [illegible], 16.6V in this case. The same voltage appears across the source of the TFT. For the transistor to turn ON, V_{GS} should be more negative than V_T. As the selected row is grounded V_G of the selected pixel transistor is zero. As a result, V_{GS} is much more negative than V_T for the transistor of the selected pixel and current flows across the OLED through the TFT.

When non-selected rows are open-circuited then a small voltage develops at these rows due to flow of small leakage currents to these rows through the column-selected pixels. Therefore, for this condition too, V_{GS} is more negative than V_T of the TFT of the column-selected pixel. Hence, there is leakage of current through the column-selected pixels.

To stop this leakage of current through the column-selected pixels the V_{GS} of the pixel transistor should be less negative than it's V_T. To achieve this the non-selected rows should be at sufficiently high DC bias so that V_{GS} of the pixel transistor becomes less negative than it's V_T.

Simulation results:

To confirm the above observations, a 60x30 modified passive matrix has been simulated for the worst case. That is, only one column is driven by a current pulse of 60μA and remaining columns are grounded. It has been found that when a bias of +15V is applied to the non-selected rows then V_{GS} (15V-16.6V) is less negative than V_T (-2V) of the transistors at column-selected pixels. In this case TFT's of the column-selected pixels remain OFF during the entire current pulse. As a result, there is almost no leakage through the column-selected pixels and I(D) of selected pixel is very close to the desired (ideal) value. Plot for I(D) selected pixel is given in figure 3.38 when input current pulse is of 60μA and figure 3.39 shows plot of I(D) selected pixel for an input pulse of 6μA. Another observation of interest here is that, due to negligible leakage of current the response time has improved significantly (≈2μs) as less number of capacitances are in the route of current flow.

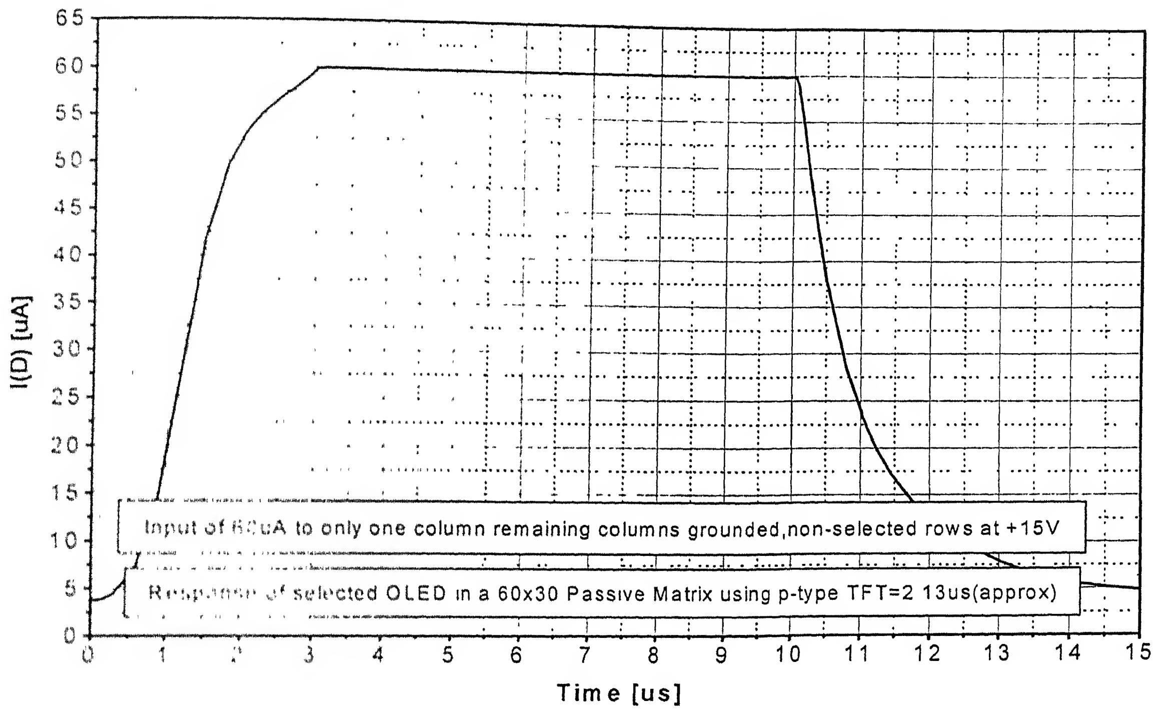


Figure 3.38 Response of selected OLED in a modified 60x30 Passive Matrix when input is 60μA

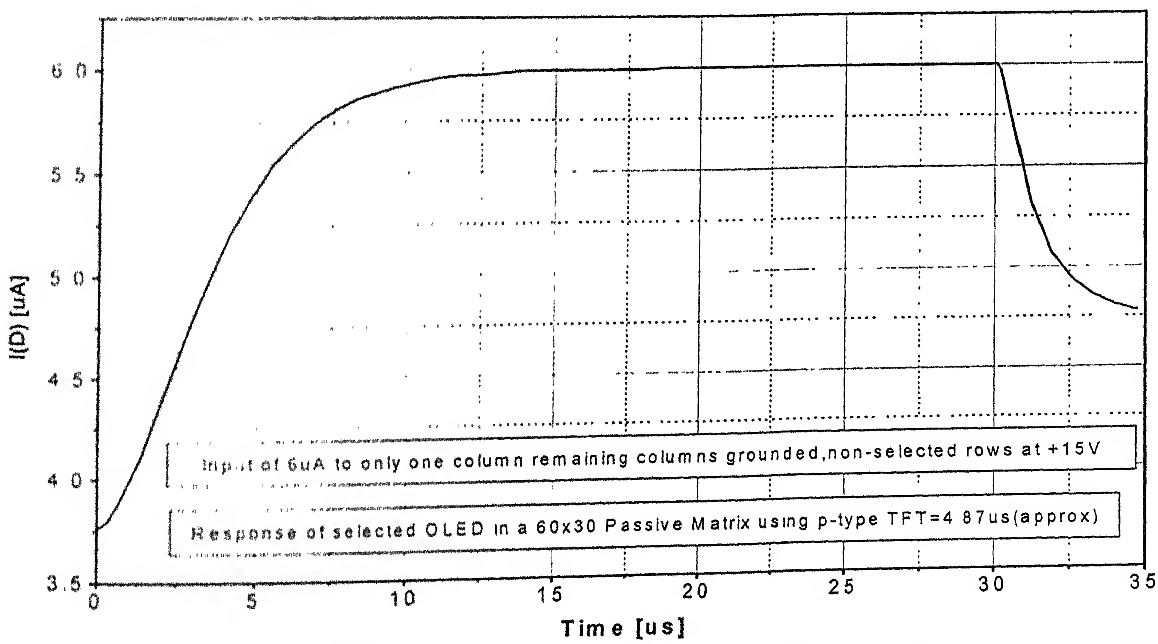


Figure 3.39 Response of selected OLED in a modified 60x30 Passive Matrix when input is 6μA

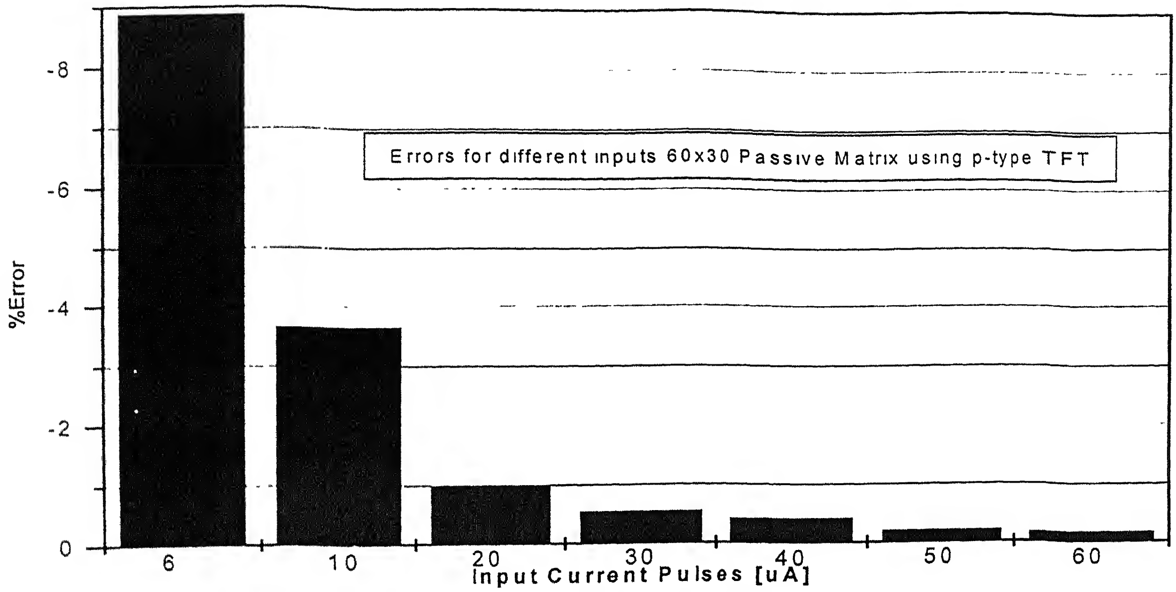


Figure 3.40 Comparison of errors in case of dynamic analysis on a modified 60x30 Passive Matrix.

To re-affirm that crosstalk is negligible in modified passive matrix different inputs as given in table 3.3 have been given to 30 columns. Remaining 30 non-selected columns have been grounded. The non-selected rows are given a bias of +15V dc. The results obtained in this case are quite heartening, as extremely small errors occur as calculated by using equations (5) and (6), for different current inputs/outputs. The percentage errors vs. input current pulse comparison is given in figure 3.40.

Simulation of a 4x3 modified passive matrix has also been done with the three rows being scanned one after another. Each row is scanned for 34.72μs starting with the first row. Current pulses of 10μA, 60μA and again 10μA, each of 34.72μs duration (ON for 30μs) are given as input one after another to column number 2 (from left). The I(D)'s of the column-selected pixels I(D2), I(D6) and I(D10) are shown in figure 3.41. There is negligible crosstalk with almost no error.

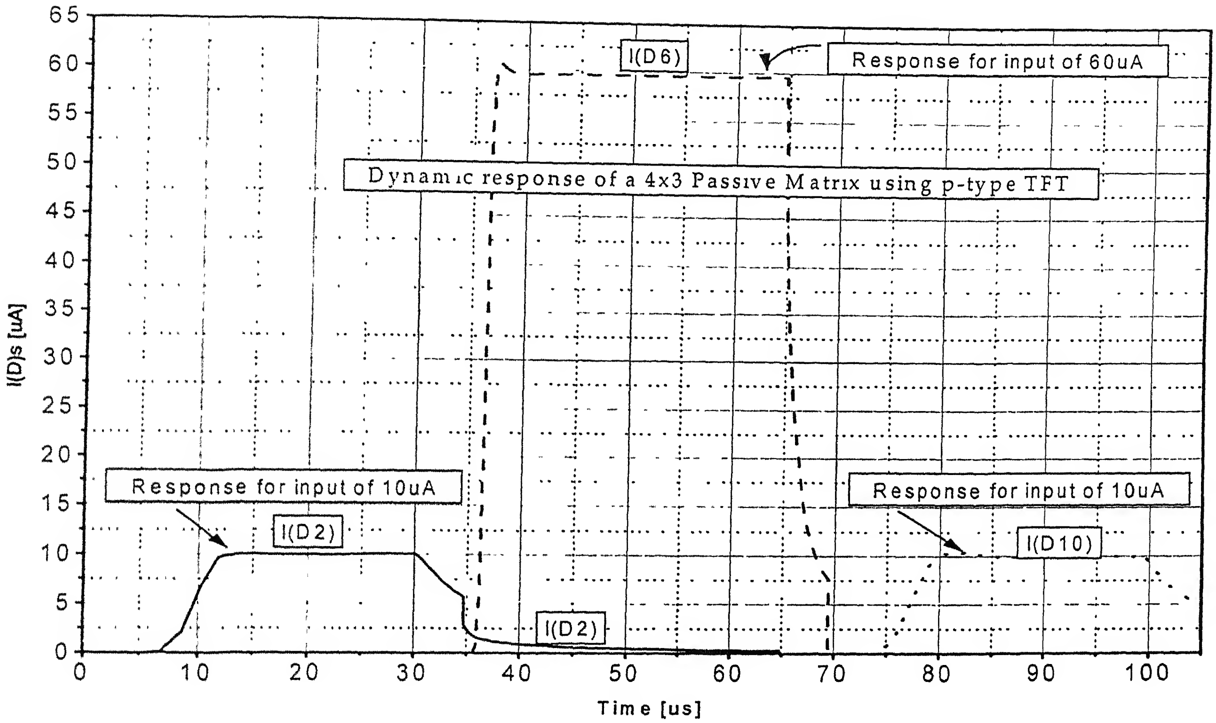


Figure 3.41 Dynamic response of a 4x3 modified Passive Matrix

CHAPTER 4

CONCLUSION AND FUTURE SCOPE

4.1 Conclusion

The intrinsic quality of OLED emissive technology is superb; high brightness and efficiency, low drive voltage and fast response time are some of the features which make it the most promising flat panel display technology of the future.

Though active matrix has been found to be more suitable for better resolution, large size and high information content displays, passive matrix can be used as a much cheaper alternative with comparable resolution in case of relatively smaller size displays if some improvements are incorporated in it's design and high performance materials are developed.

This thesis has explored the characteristics of OLED and it's performance in passive matrix of different sizes, under different conditions, as the main aim was to identify reasons for crosstalk so that a more efficient passive matrix can be designed. Dynamic response of an OLED has been studied in detail under different conditions by means of circuit simulations. It is observed that response time of an OLED is inversely proportional to the drive current and it's response in display panels depends on the number of rows in the display. Crosstalk in dynamic mode has been compared with crosstalk in DC mode of operation for similar conditions. Flow of currents through different pixels has also been studied under different conditions in order to identify reasons for crosstalk in dynamic mode of operation of passive matrix. It is seen that in the dynamic mode of operation crosstalk occurs primarily due capacitances of non-addressed pixels and as ON time of the drive current pulse is increased error in actual output in dynamic mode approaches error obtained in case of DC mode of operation. It is also seen that

when a reverse bias is applied to non-selected rows error in actual output is less. In this case response time of pixels is also small. But crosstalk is not completely eliminated.

A modified pixel model has been developed. Simulations performed on passive matrix using modified pixels show that this modification eliminates crosstalk quite appreciably and has much better response time.

4.2 Scope for Future Work

As the organic display technology is at present in a developing stage there is still scope for lot of improvement of this technology, whether it is development of high performance materials or better matrix designs.

As this work focussed primarily on crosstalk due to leakage of currents in dynamic mode of operation, other issues of crosstalk in passive matrix such as electrode resistance, location of faulty pixels, poor rectification ratios of OLEDs are required to be studied and techniques need to be developed to eliminate crosstalk due to these reasons.

The modified pixel design developed in this work needs improvement in order to reduce power requirement. The p-type poly-Si TFT used in this work needs to be replaced by a better performance TFT. A p-type organic transistor, if incorporated in the passive matrix will result in an "all organic display". Moreover, schemes to incorporate full colour in organic passive matrix displays need to be developed.

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SPICE Parameters of a Typical p-type Poly-Si TFT

Parameter	Value
CBD	0
CGDO	5e-15
CGSO	5e-15
Delta	0
Eta	0
FC	0.5
Gamma	0
IS	10e-15
Kappa	0.2
KP	10e-9
L	5e-6
Level	1
MJ	0.5
N	1
PB	0.8
Phi	0.6
RB	0
RD	0
RDS	32e9
RG	0
RS	0
Theta	0
T_{ox}	300e-9
V_{MAX}	0
V_{TO}	-2
W	300e-6
XJ	0

Appendix B

Specifications of OLED Passive Matrix developed by Ritek

Mechanical Specifications

	64 x 48	64 x 64	256 x 64	128 x 64
Panel Size	12.93 x 39.5mm^2	12.5 x 42.5mm^2	95 x 33.93mm^2	86 x 52.2mm^2
Dot Size	0.38 x 0.38 mm^2	0.38 x 0.38 mm^2	0.26 x 0.28 mm^2	0.48 x 0.48 mm^2
Gap	0.04mm	0.04mm	0.03mm	0.04mm
Pitch	0.42mm	0.42mm	0.29mm, 0.31mm	0.52mm
View Area	26.88 x 20.16mm^2	26.88 x 26.88mm^2	74.24 x 19.84mm^2	66.52 x 33.22mm^2
Duty	1/48	1/64	1/64	1/64

Electro-Optical Specifications

	64 x 48	64 x 64	256 x 64	128 x 64
Pixel Luminance	60 cd/m2@9 volts 1/48 duty	45 cd/m2@9 volts 1/64 duty	45 cd/m2@9 volts 1/64 duty	45 cd/m2@9 volts 1/64 duty
CIE coordinates	x=0.25 y=0.68	x=0.25 y=0.68	x=0.25 y=0.68	x=0.25 y=0.68
Contrast	>100:1	>100:1	>100:1	>100:1
Pitch	0.42mm	0.42mm	0.29mm, 0.31mm	0.52mm
View Angle	>160 degree	>160 degree	>160 degree	>160 degree